Measurements of scintillation and ionization signals from low-energy liquid argon nuclear recoils with the ReD experiment

Edivaldo Moura Santos
Physics Institute - University of Sao Paulo
on behalf of the DarkSide-20k Collaboration

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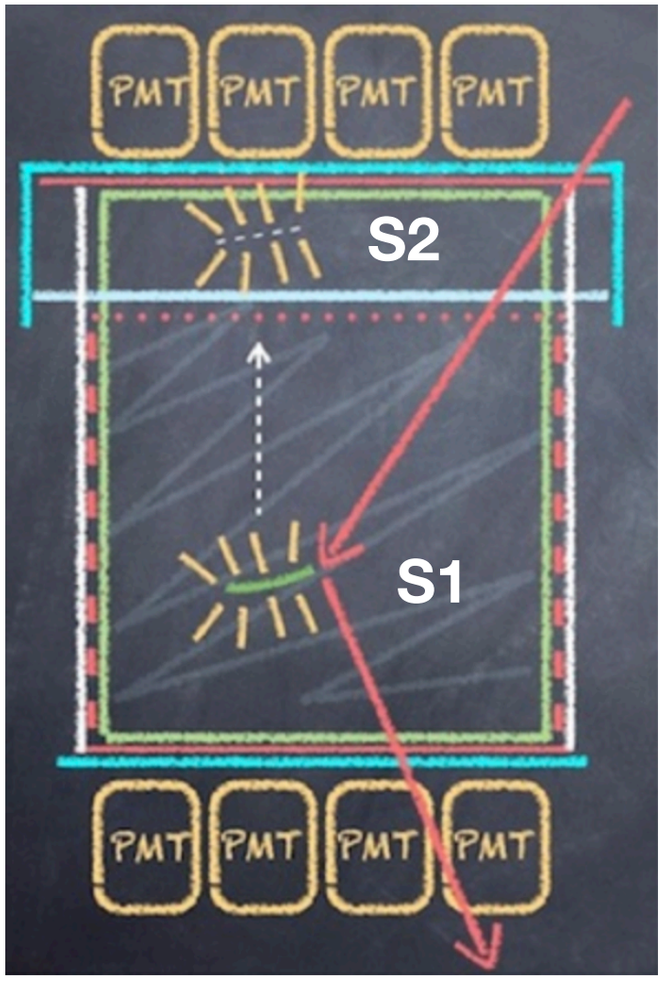
Motivation

- WIMP searches for masses below 10 GeV/c^2 lead to O(1 keV) nuclear recoils (NRs).
- At these energies, experiments based on dual-phase TPCs should rely on S2-only events (S1 is too weak).
- Ionization yield for NRs poorly known for argon at O(1 keV) energies.
- Dedicated measurements of ionization yields for LAr NRs is therefore essential to overcome systematic uncertainties.



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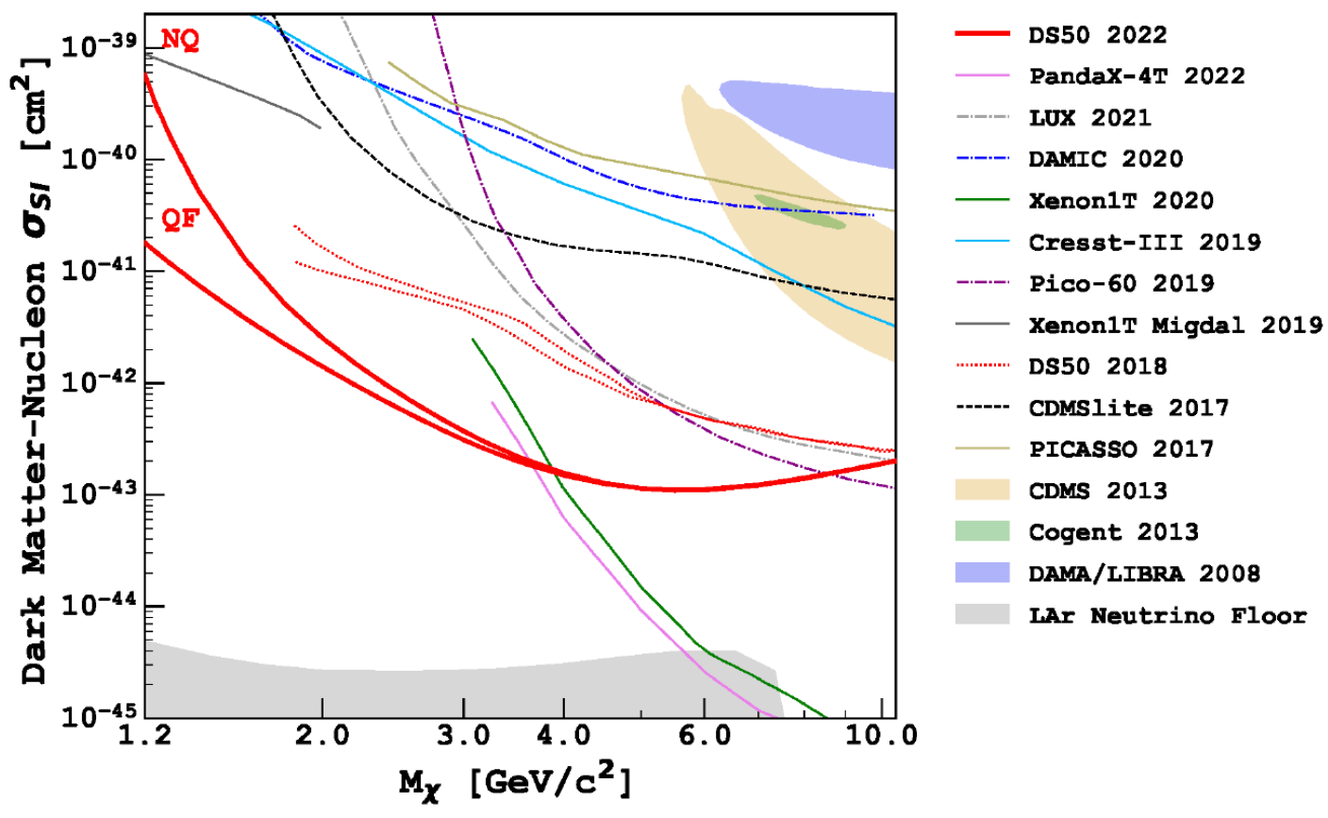
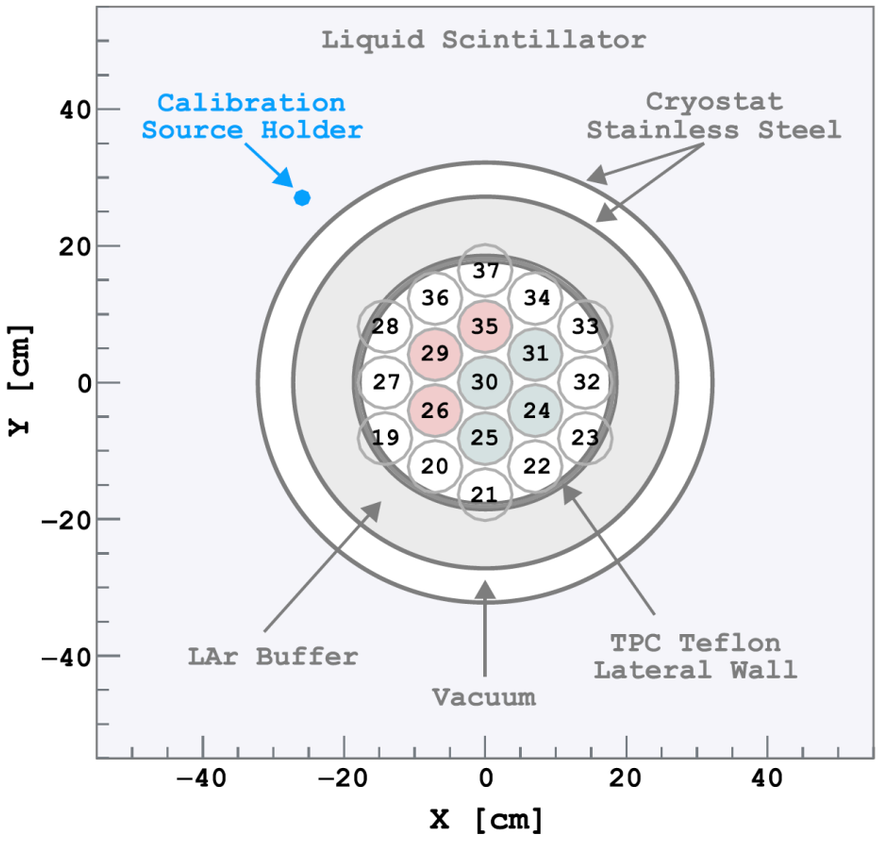
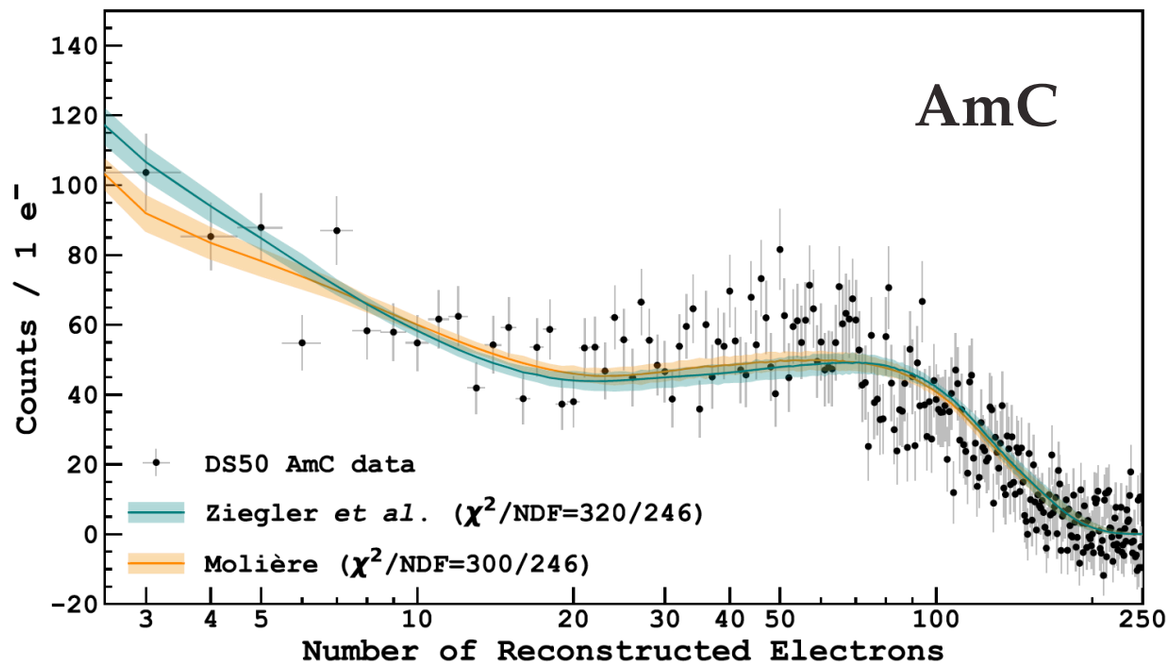


Ionization yields from nuclear recoils in DS-50

- AmC and AmBe dedicated runs with UAr in DS50.
- Lowest NR calibration threshold ever achieved in LAr → 435^{+47}_{-34} eV$_{er}$ ~ 3 electrons !





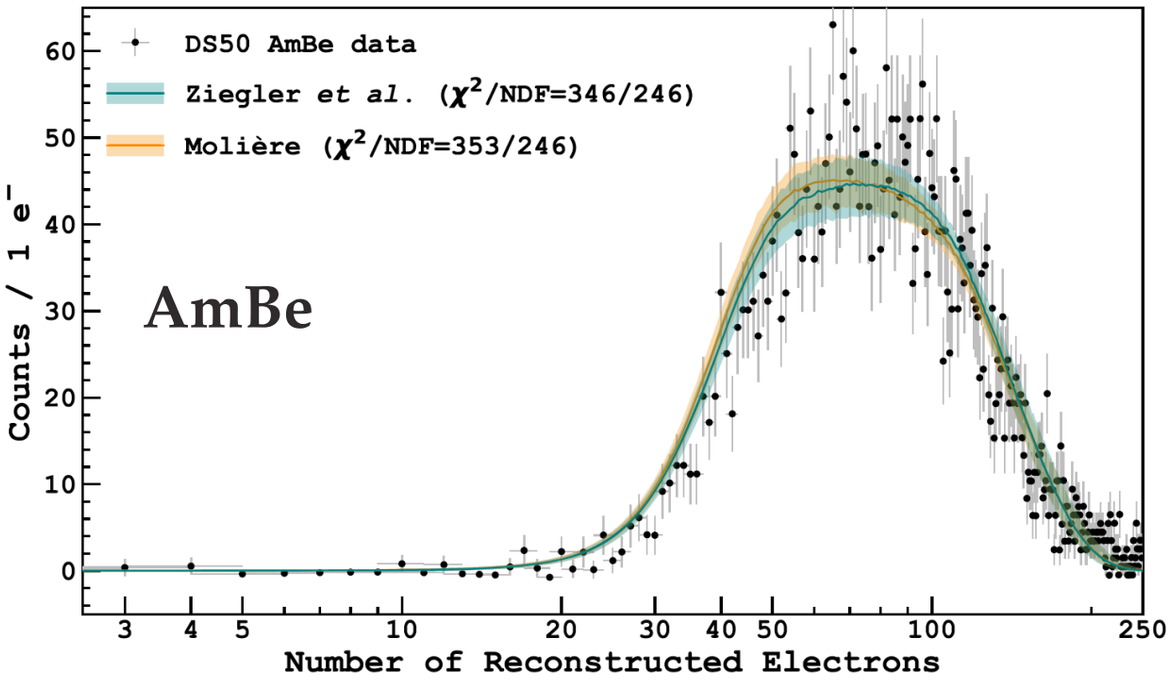
- Number of ionization electrons from S2:

$$N_{\text{i.e.}} = \frac{S2}{g2}$$

- Reconstructed recoil energy from S1 and S2:

$$E_{\text{er}} = w\left(\frac{S1}{g_1} + \frac{S2}{g_2}\right)$$

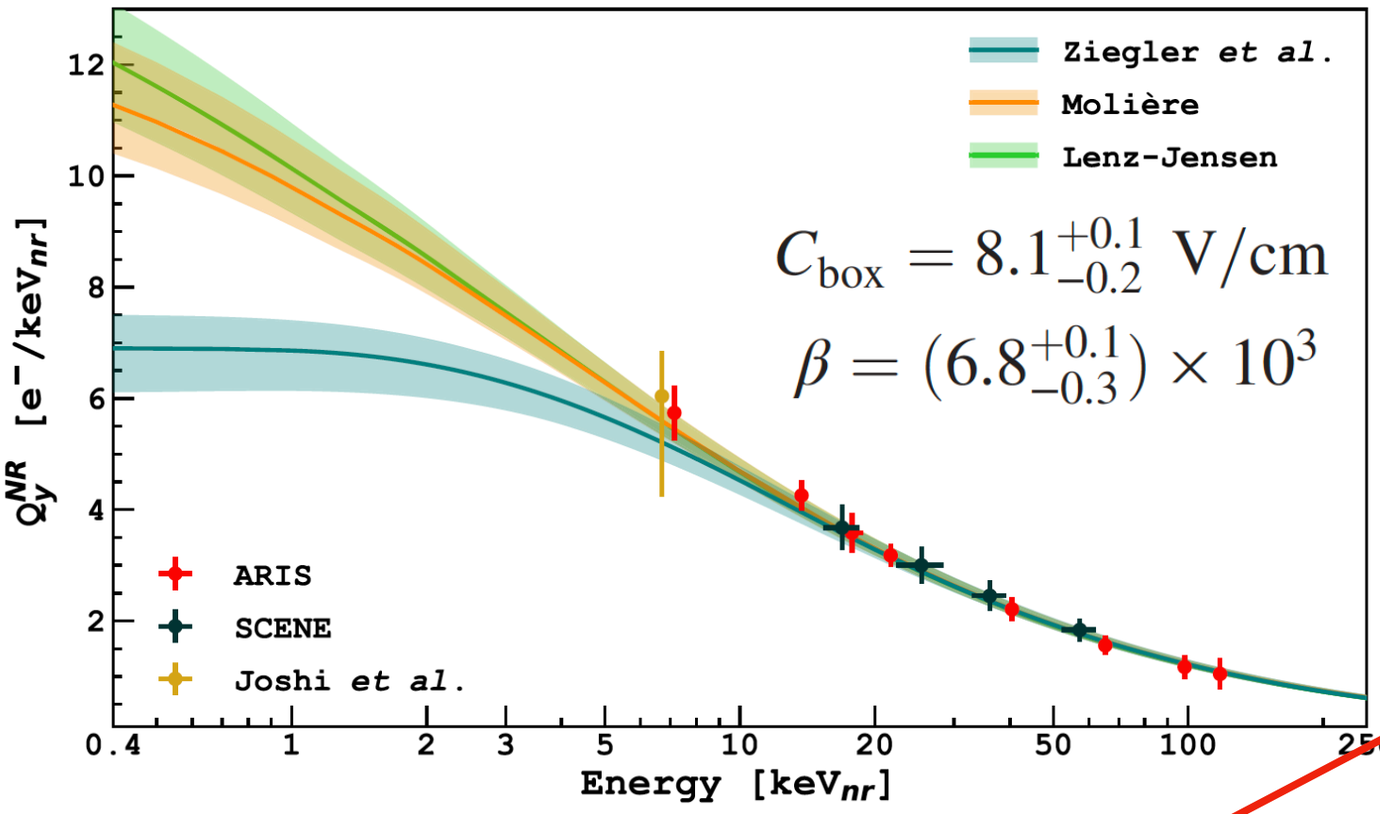
$$g_1 = 0.16 \pm 0.01$$
$$g_2 = 23 \pm 1 \text{ pe}/e^-$$
$$w = 19.5 \pm 1.0 \text{ eV}$$



DS50 Coll. PRD 104, 082005 (2021)

Ionization yields from nuclear recoils in DS-50

- Excellent agreement with external data from ARIS and SCENE



NR ionization yield:

$$Q_y^{\mathrm{NR}} = \frac{N_{\mathrm{i.e.}}}{E_{\mathrm{nr}}} = \frac{(1-r)N_i}{E_{\mathrm{nr}}}$$

Survival probability (**Thomas-Imel**):

$$1 - r = \frac{1}{\gamma N_i} \ln(1 + \gamma N_i)$$

$$\gamma \equiv \frac{C_{\mathrm{box}}}{E_{\mathrm{drift}}}$$

200 V/cm @ DS

Fit to data with 2-parameters

Example of nuclear quenching model (**Ziegler**):

$$N_i = \beta \kappa(\epsilon) = \beta \frac{\epsilon s_e(\epsilon)}{s_n(\epsilon) + s_e(\epsilon)}$$

Nuclear and electronic stopping powers

- Current systematic uncertainty dominated by nuclear quenching models below 5 keV$_{\mathrm{nr}}$

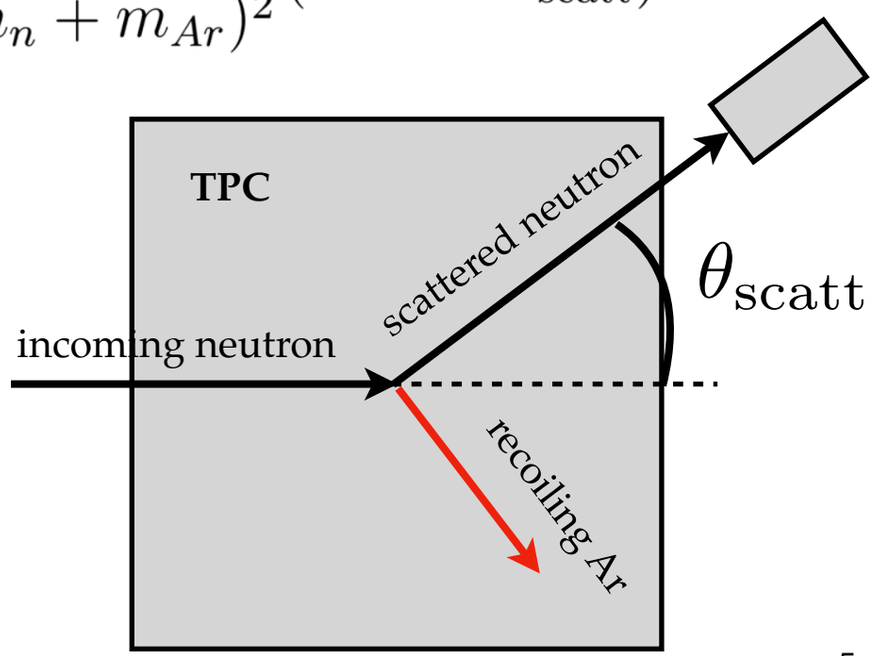
DS50 Coll. PRD 104, 082005 (2021)

The case for low-energy NRs with ReD

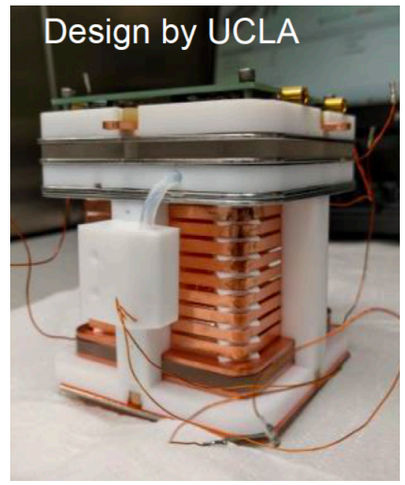
- DS50 NRs measurements with AmC and AmBe lack constraining power on quenching models below 5 keV_{nr}.
- Reducing the room for those models at low energies needs accurate and direct measurements of recoiling energy and ionization yield (i.e. less Monte Carlo dependence).
- The **Recoil Directionality (ReD)** is a project within the **Global Argon Dark Matter Collaboration (GADMC).**
- One of ReD's goal is to perform NR ionization yields in LAr in the **energy range 2-5 keV**.
- A miniaturized version of DS50 TPC is the main detector to provide the S1's and S2's.

2-body kinematics approach + ToF-based energy measurements

$$E_r = 2E_n \frac{m_n m_{Ar}}{(m_n + m_{Ar})^2}(1 - \cos\theta_{\text{scatt}})$$

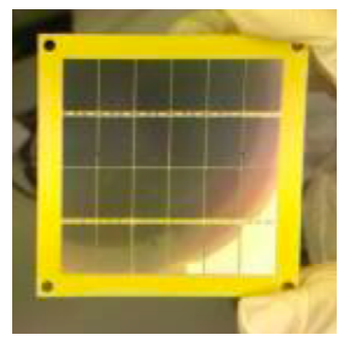


5 (L) x 5 (W) x 6 (H) cm^3

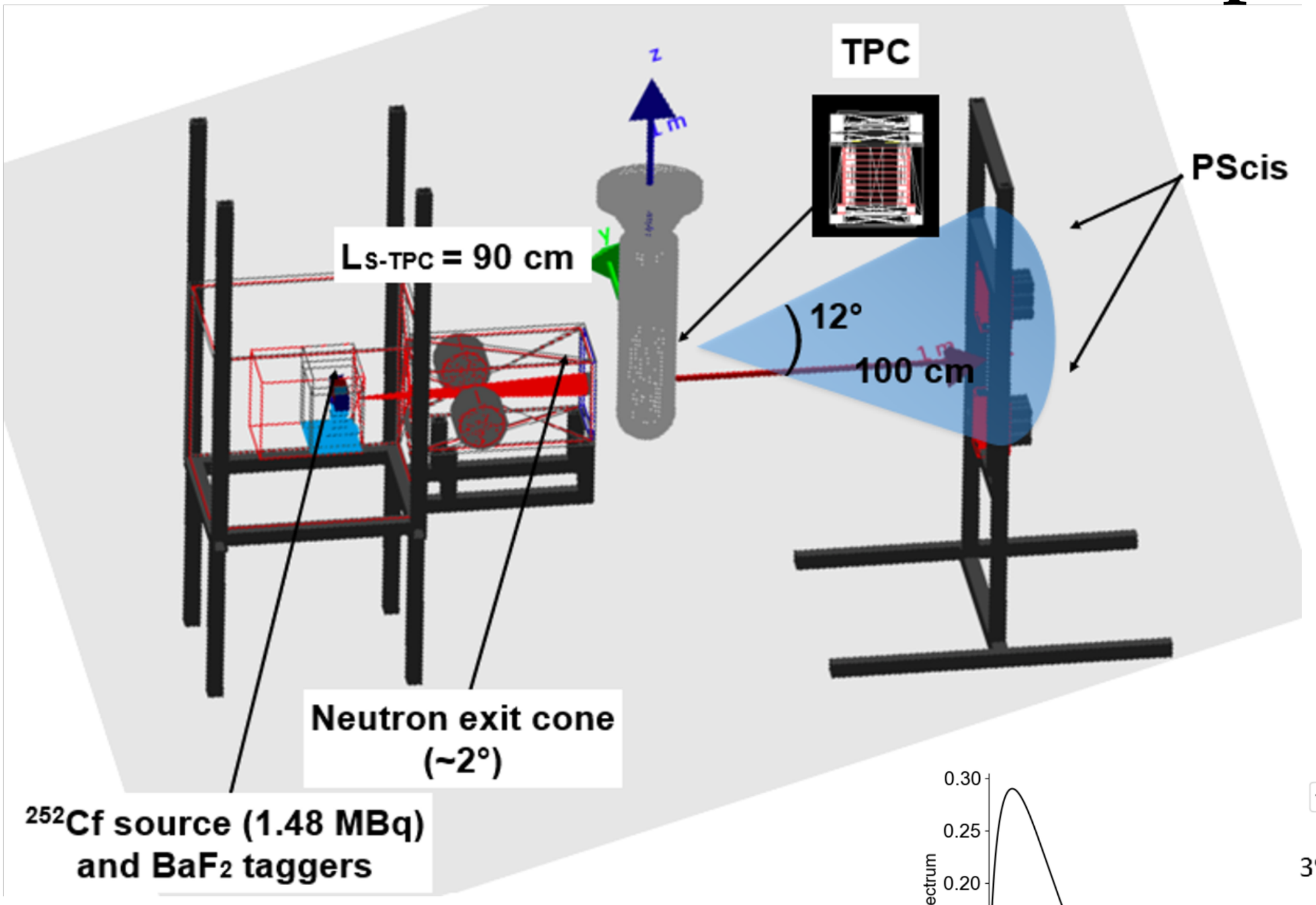


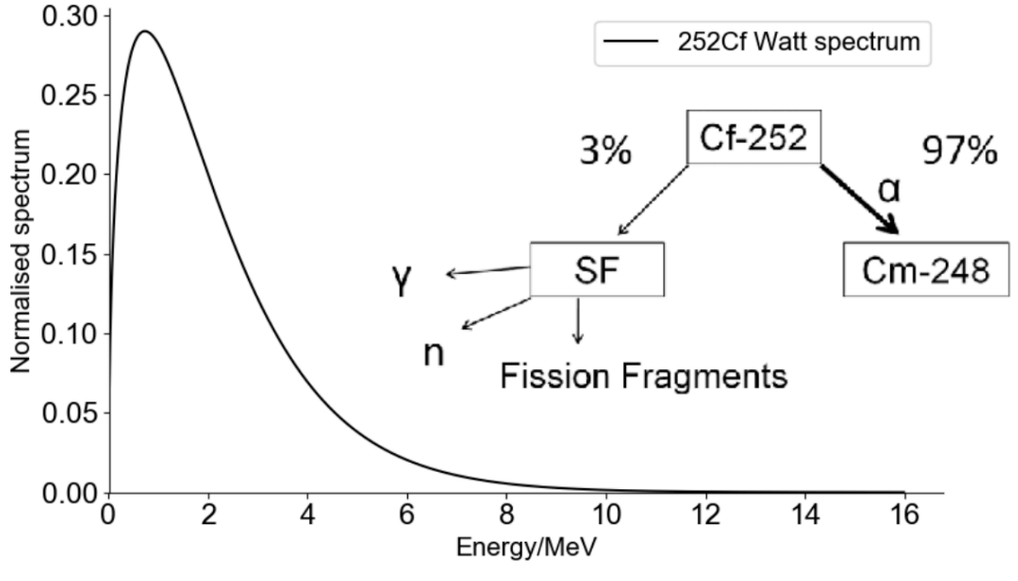
SiPM light readout systems

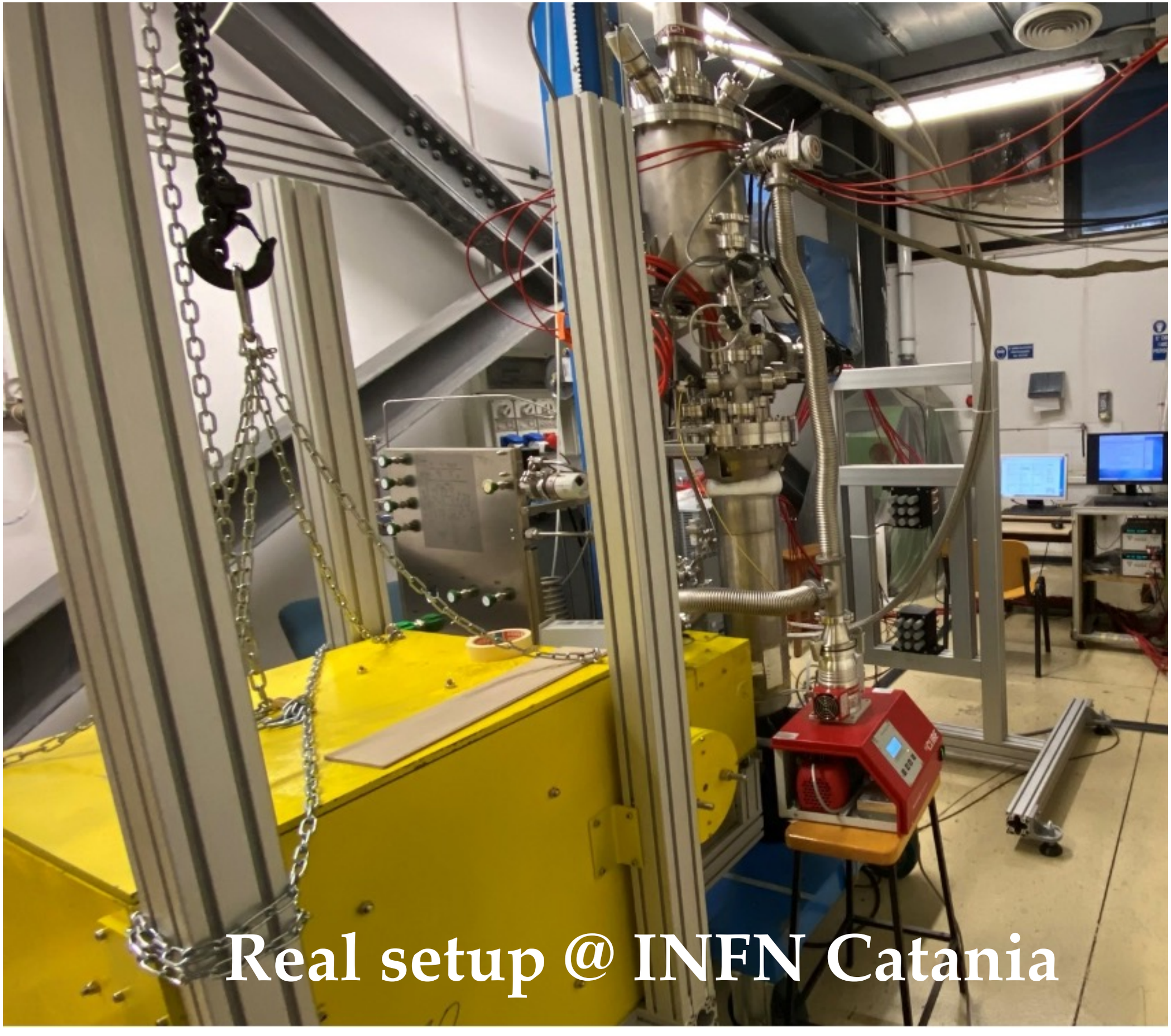
24 chan. (top) + 1 chan. (bottom)



ReD's radioactive sources campaign







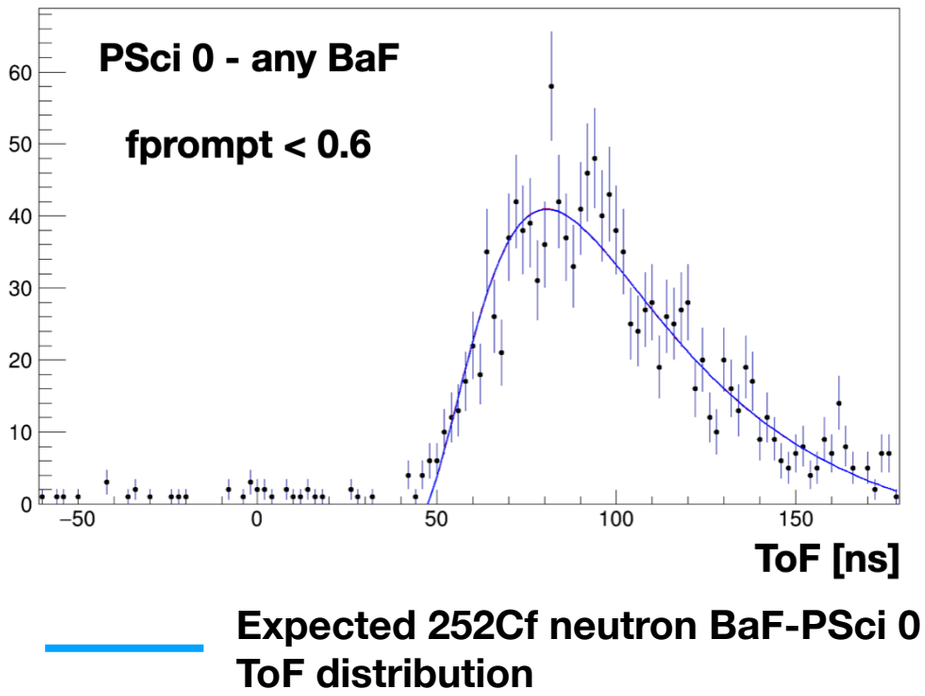
Real setup @ INFN Catania

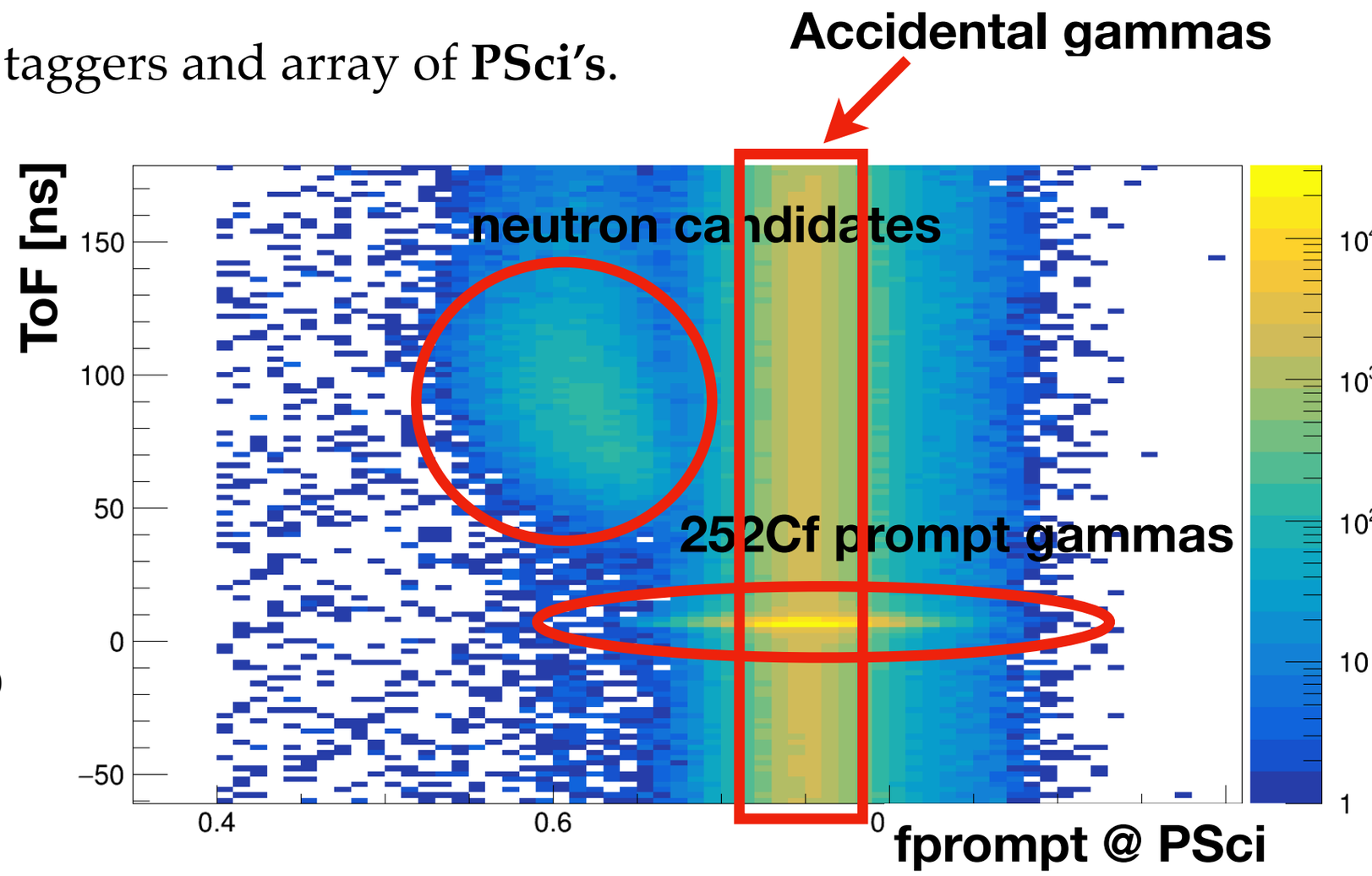
Data taking conditions

- Period: Jan 10th - Mar 16th, 2023
- Trigger algorithm: (BaF1 || BAF2) && “any PSci”
- TPC operated in slave mode (S1 may be to feeble to trigger)
- Calibration at a weekly basis with laser and 241Am and 137Cs
- TPC non-homogeneities corrected with calibration and background runs
- Rate ~ 2.5 Hz (600 GB/day)
- Background = gamma rays and accidentals
- E_{drift} = 200 V/cm
- E_{el} = 5.79 kV /cm
- S2 pattern on top PMT array => (x,y) coordinates
- Drift time => z coordinate

Particle identification

- ToF distribution from the 2 BaF taggers and array of **PSci's**.

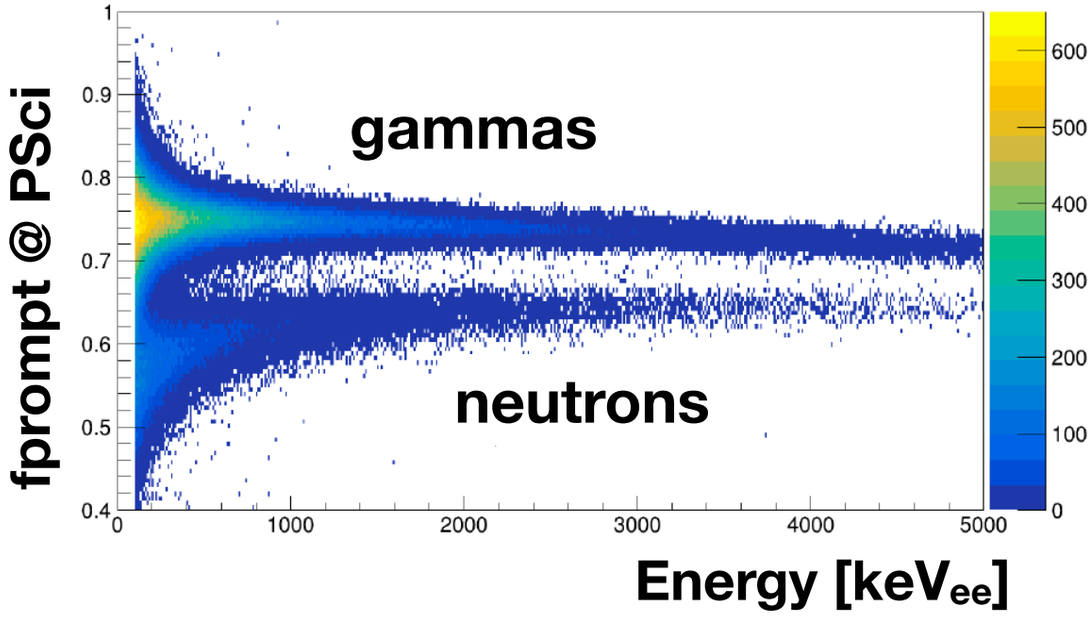




$$\Delta_{\mathrm{ToF}} \sim 0.7 \text{ ns} \Rightarrow \frac{\Delta E_n}{E_n} \lesssim 5\%$$

- γ contamination $< 1\%$ using the PSci's (EJ-276) PSD capabilities.

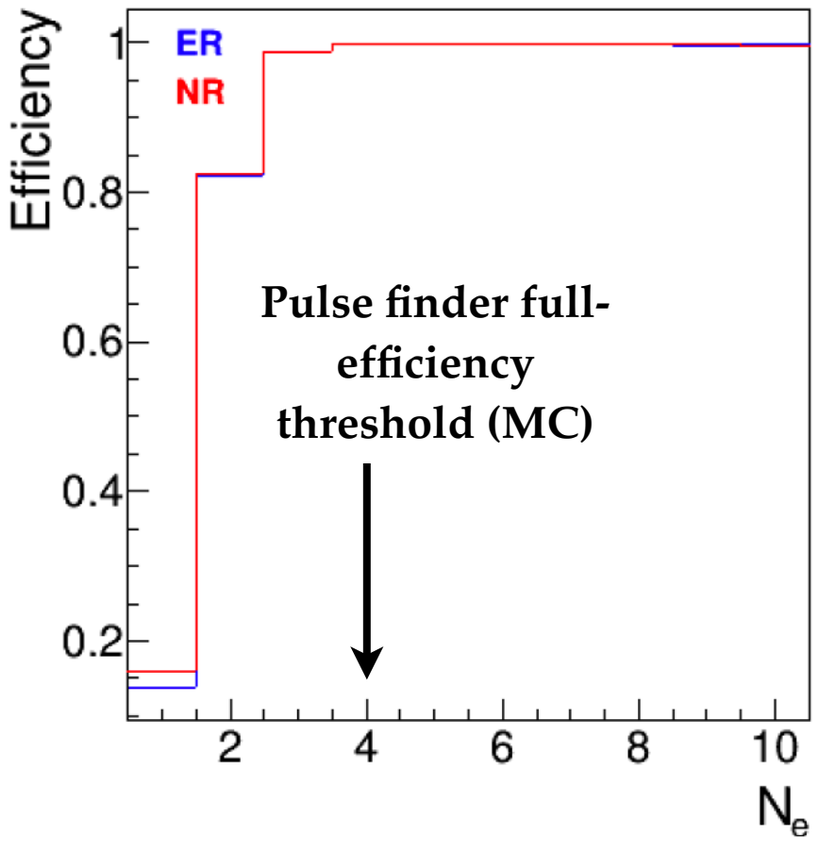
$$\mathrm{fprompt} \equiv \frac{Q_{\mathrm{short}}}{Q_{\mathrm{long}}}$$

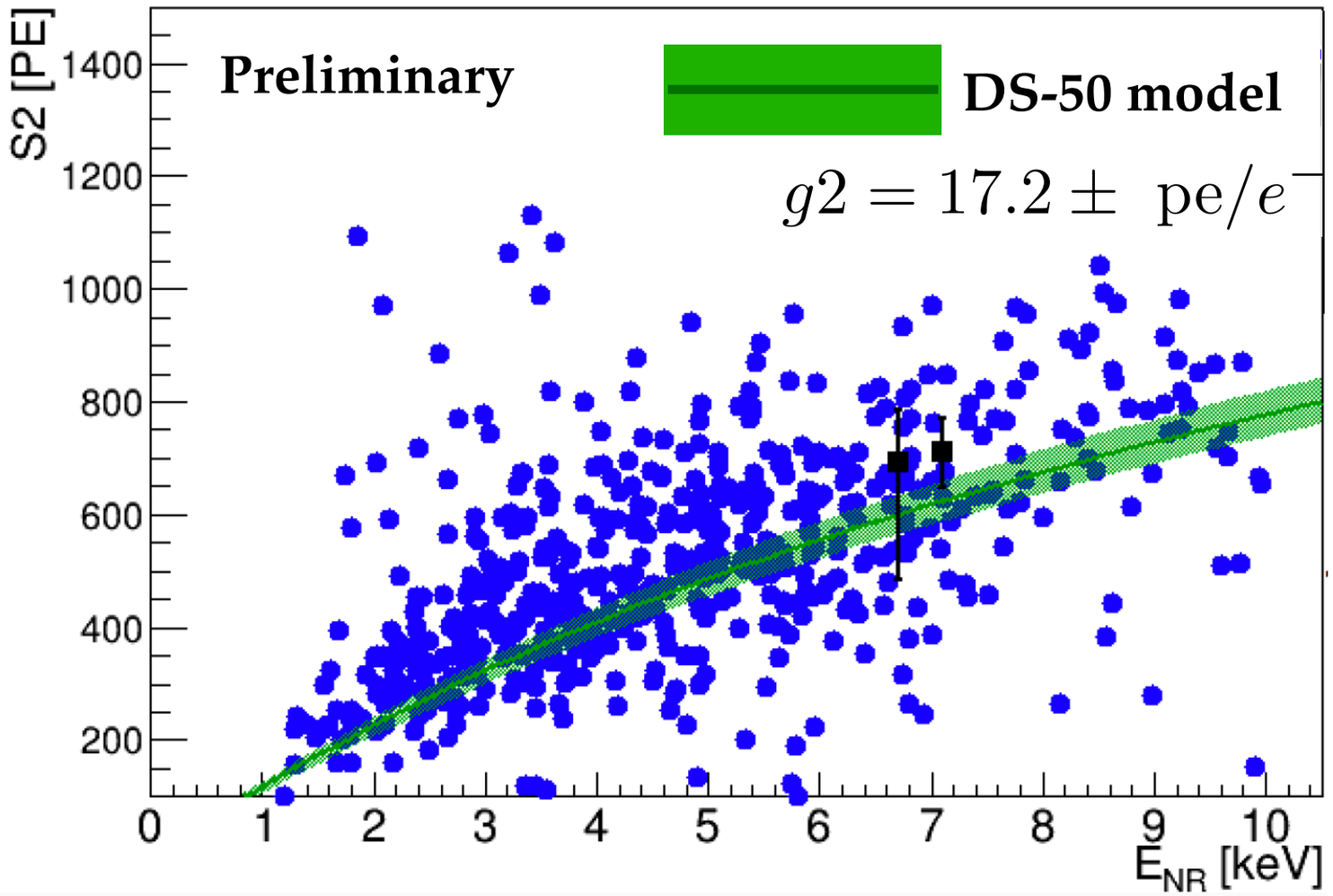


Final sample @ TPC

- S1+S2 → f100>0.5 || S1 < 100 pe
- S2only → Tstart > 5 μs && Tstop < 78 μs
- $\Delta T(S2\text{-}BaF) < \max(T_{drift}) = 65$ μsec
- BG before 1st pulse and after last pulse < 1.5 spe/μs
- (x,y) in the central 4x4 cm region
- S2 (XYT corrected) < 3000 [spe]

873 events after all cuts
(~74% S2-only)





- S2-only events lead to target threshold of nuclear recoil energies of 1-2 eV_{nr}

The next phase: ReD+

GOAL: To perform an independent measurement of low energy nuclear recoils with a mono-energetic neutron beam at ReD.

- Neutrons generated in low-energy DD reactions:

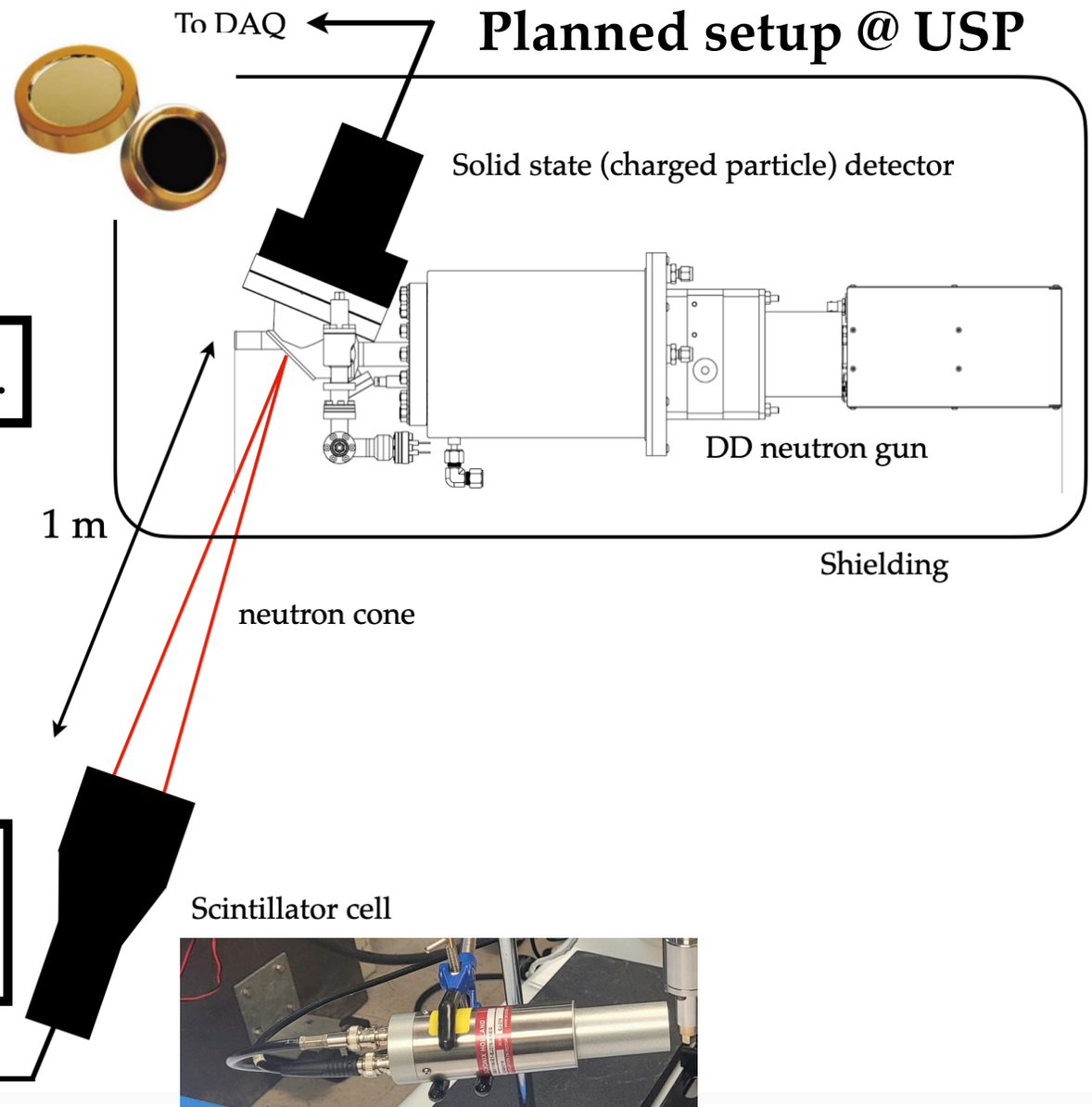
$$^{2}_{1}\mathrm{D} + {}^{2}_{1}\mathrm{D} \rightarrow {}^{3}_{1}\mathrm{T}\,(1.01\ \mathrm{MeV}) + p^{+}(3.02\ \mathrm{MeV}) \quad 50\%$$
$$\rightarrow {}^{3}_{2}\mathrm{He}\,(0.82\ \mathrm{MeV}) + n^{0}(2.45\ \mathrm{MeV}) \quad 50\%$$

Time-tagging the associated 3He inside the gun.

Neutron cone

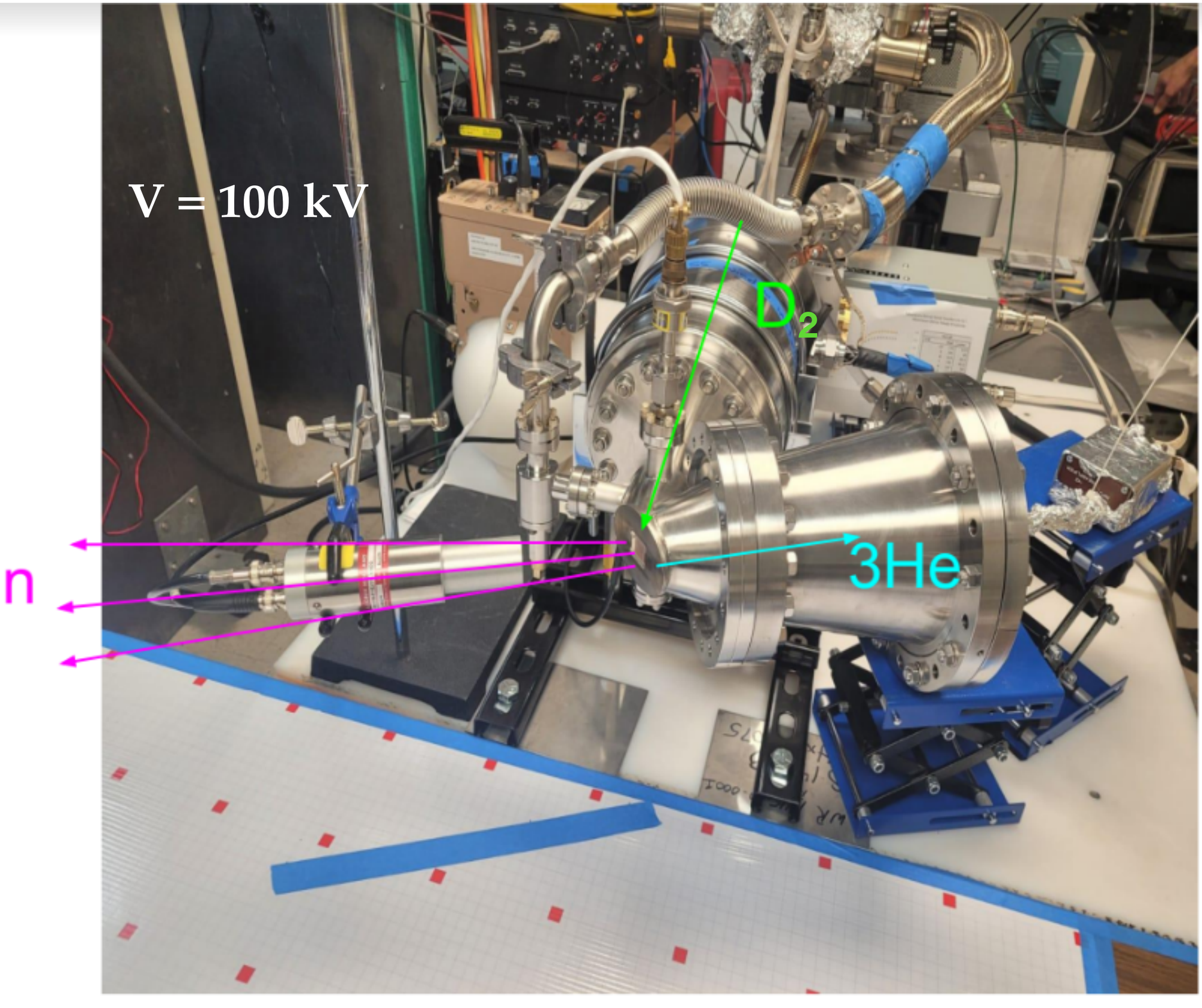
Lower background rate due to interaction with TPC inactive material

Planned setup @ USP



- Funding for the NG commissioning approved by FAPESP in SP.

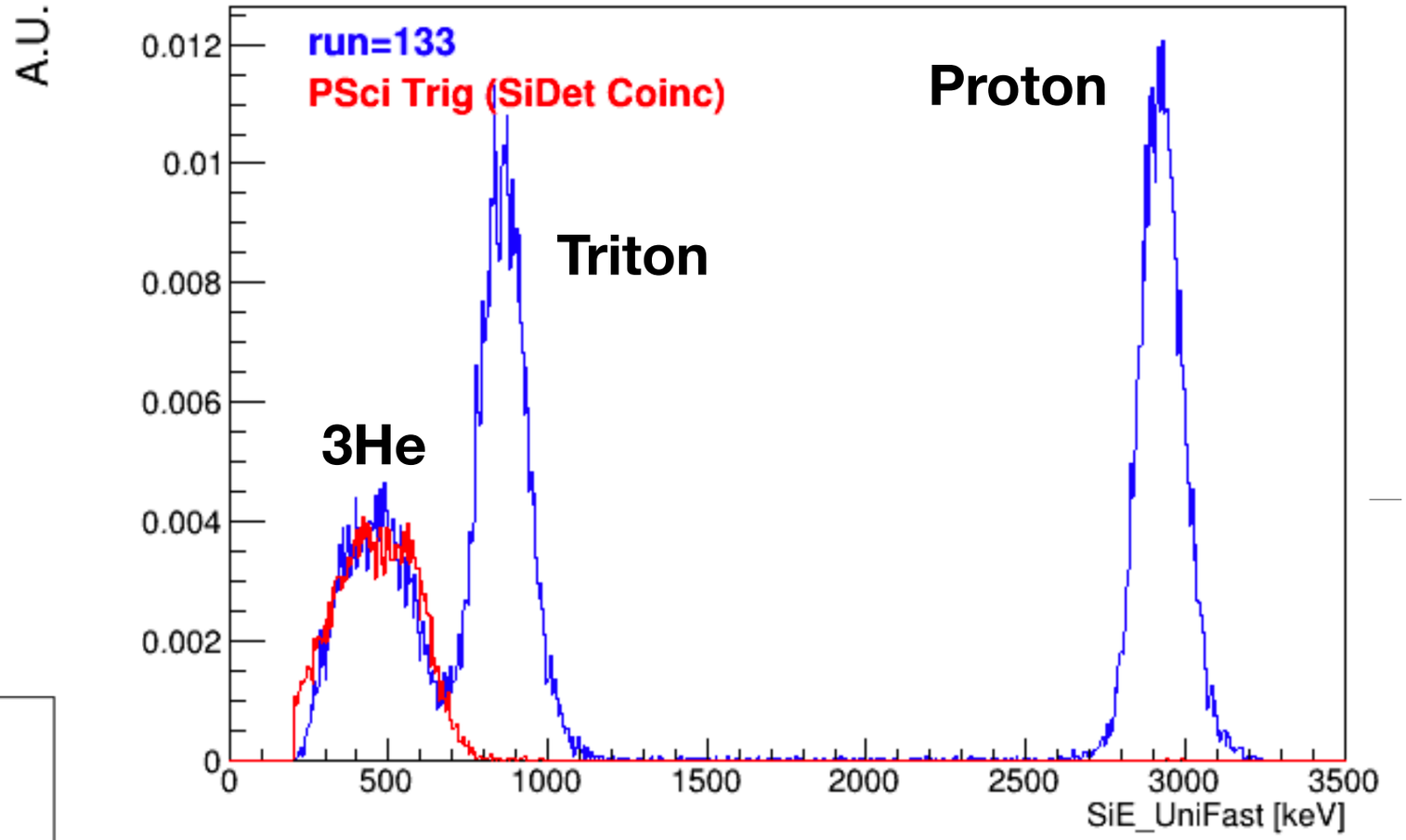
Proof of concept @ Adelphi Inc. (Oct. 2023)

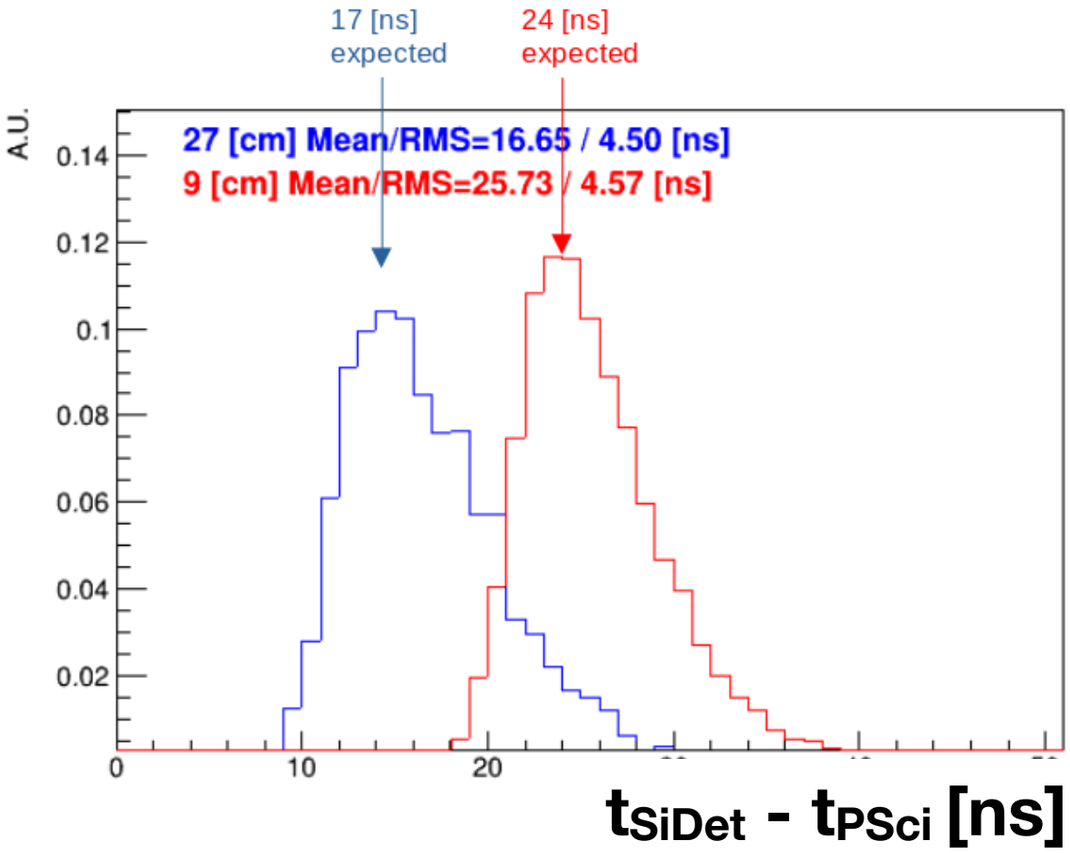


3He-neutron coincidences

Very clean coincidence signal (no need of PSD in the PSci to isolate the signal, only a 200 ns coincidence window).

- PSci Energy: (50,1000) keV
- -100< t_{sidet} -t_{psci} <100 [ns].





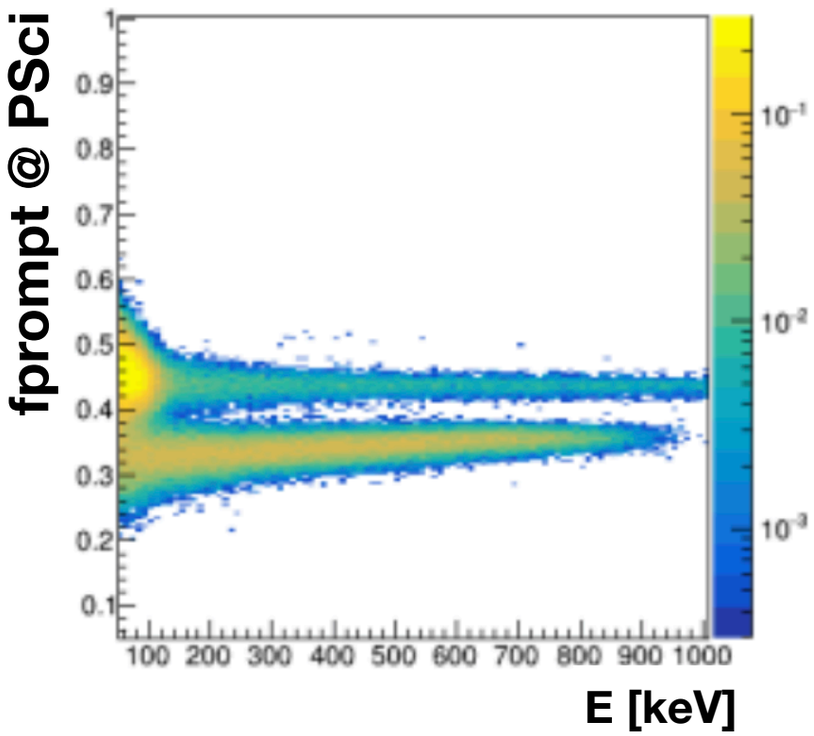
Shift of 8 ns in peaks of ToF distributions for 2 PSci-target distances (9 cm and 27 cm) consistent with expected delay for a 2.58 MeV neutron.

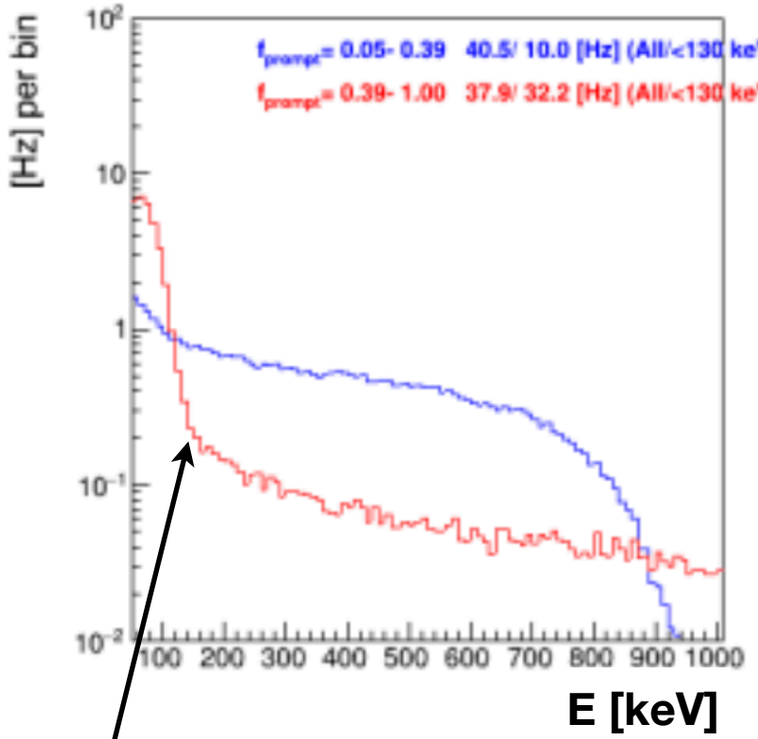
X-ray contamination under control

Adelphi's ReD+ campaign

Trigger at the PSci

Run 147 ~27 cm from target



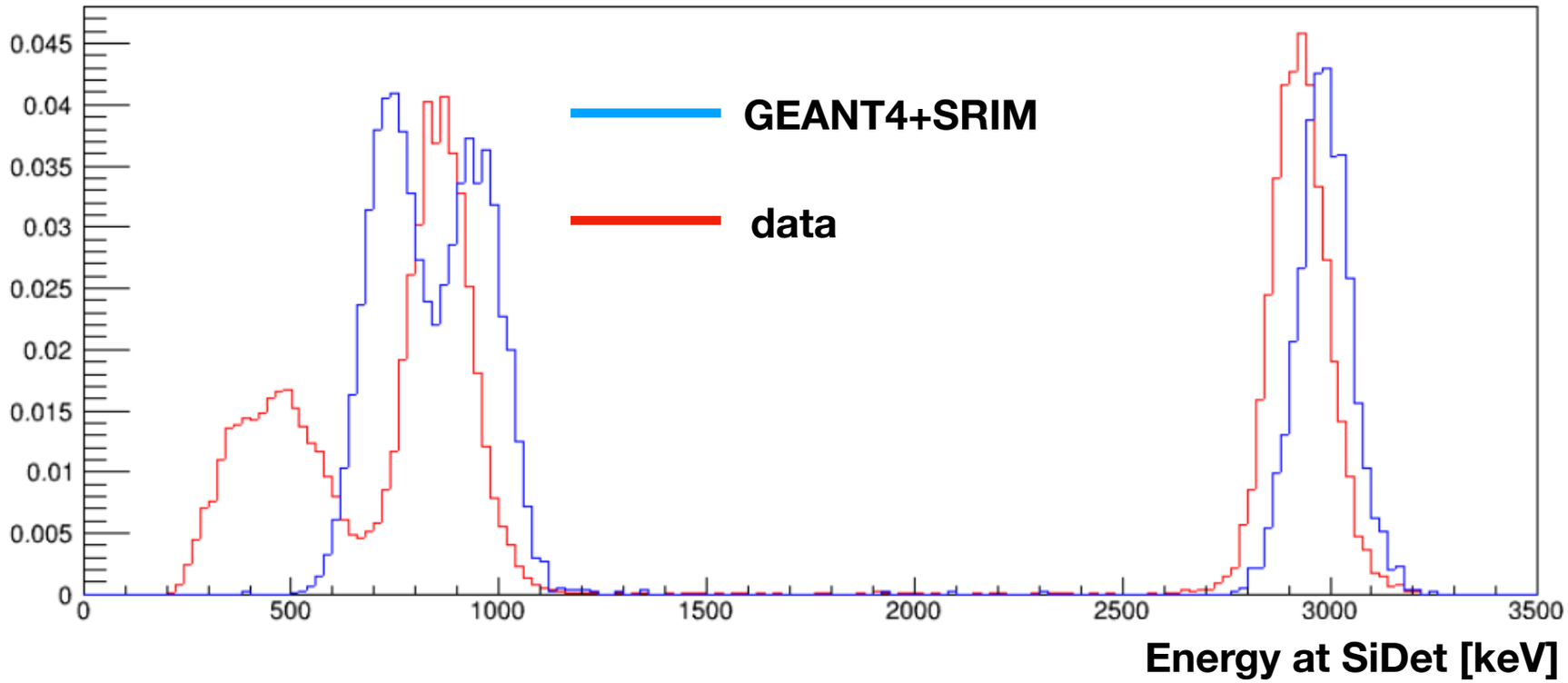


X-rays with sharp energy cutoff at ~100 keV !

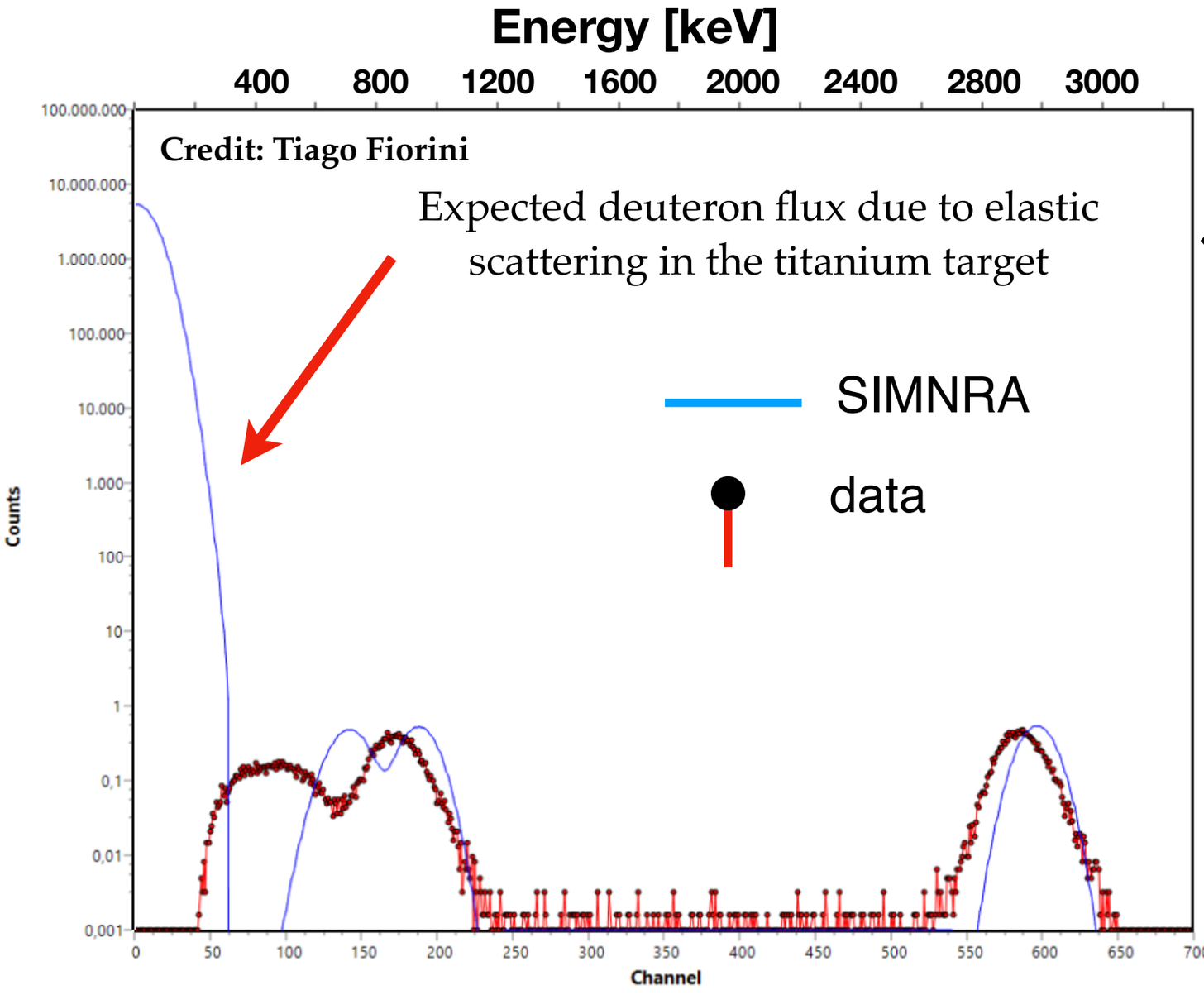
- Adelphi's DD107 NG has very low production of X-rays through bremsstrahlung.
- Beam optics seems well designed.

Unexpected issues

- Measured 3He peak position (470 keV) turned out lower than expected (737 keV).



- The data/simulation mismatch in the 3He peak could be due to the formation of a deep dead layer (~0.5 μm) in the silicon detector.
- During the campaign at Adelphi, we believe the detector has been exposed to a high rate (~MHz) of low-energy (< 200 keV) deuterons elastically scattered off the titanium target.

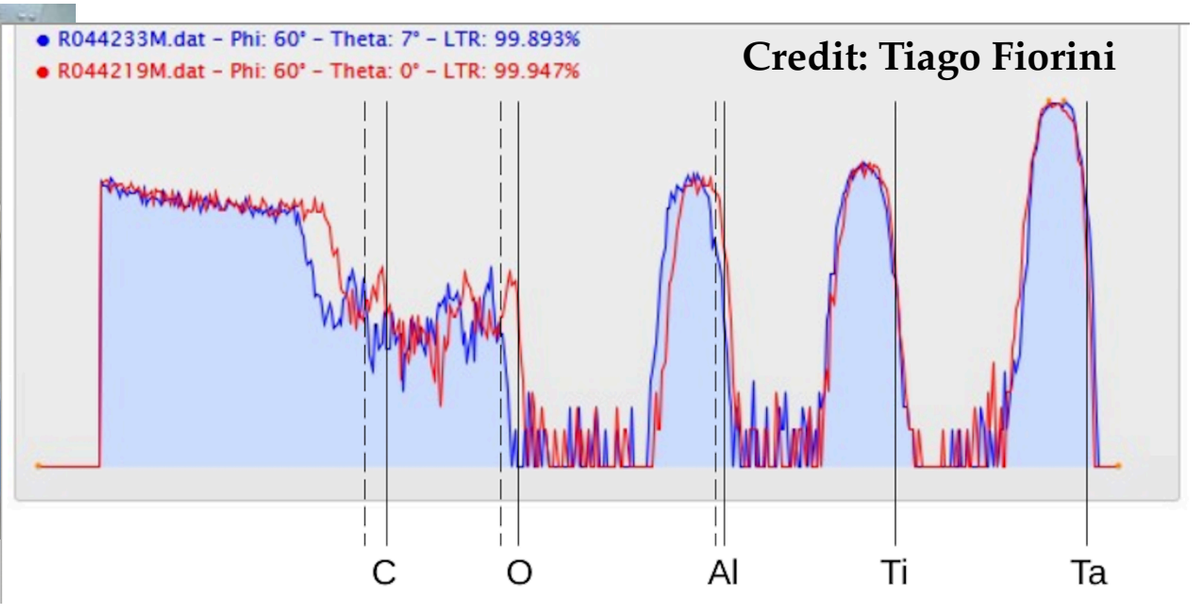


Independent calculations of expected signal with SIMNRA

SiDet dead layer hypothesis consistent with Rutherford backscattering measurements with an α-beam from a TANDEM at USP and a reference thin film of known atomic composition.

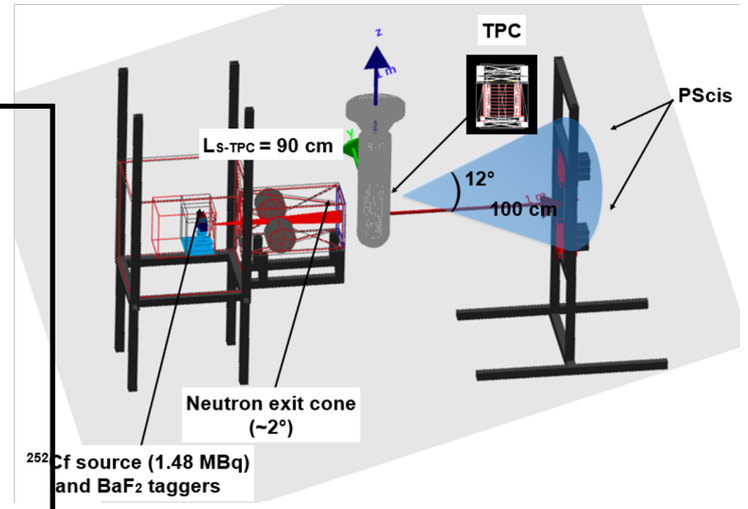
SiDet 1 (Adelphi campaign)

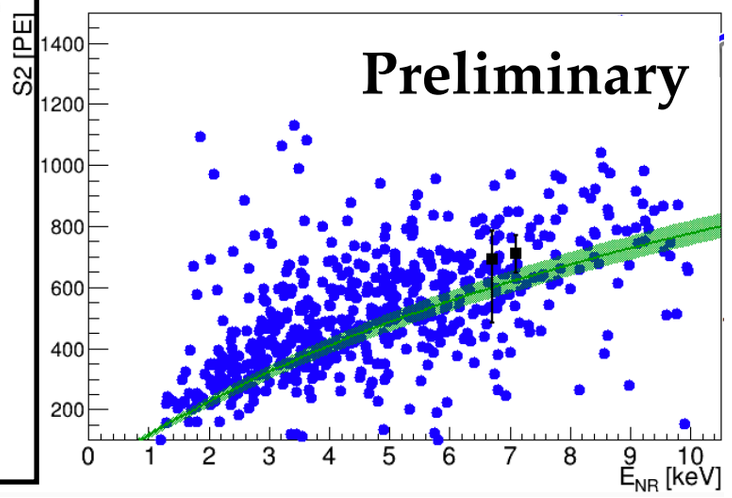
SiDet 2

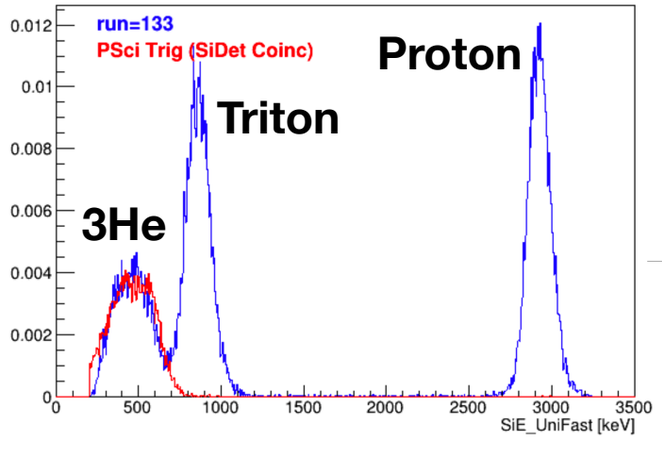


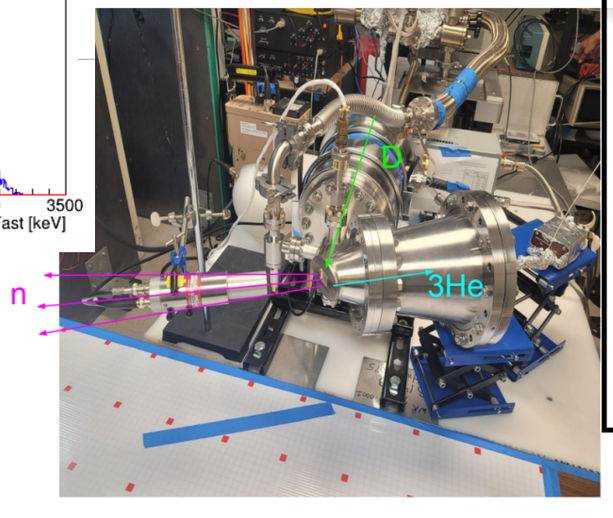
Summary

- ReD's 252Cf campaign at INFN, Catania successfully identified LAr nuclear recoils inside a miniaturized dual-phase TPC down to a few keV_{nr} .
- TPC designed by UCLA, characterized and commissioned at Naples University
- ToF techniques and 2-body kinematics employed for neutron energy reconstruction.
- Final sample of 820 NRs events selected.
- S2 x recoil energy preliminary comparison with expectations based on DS-50 model.





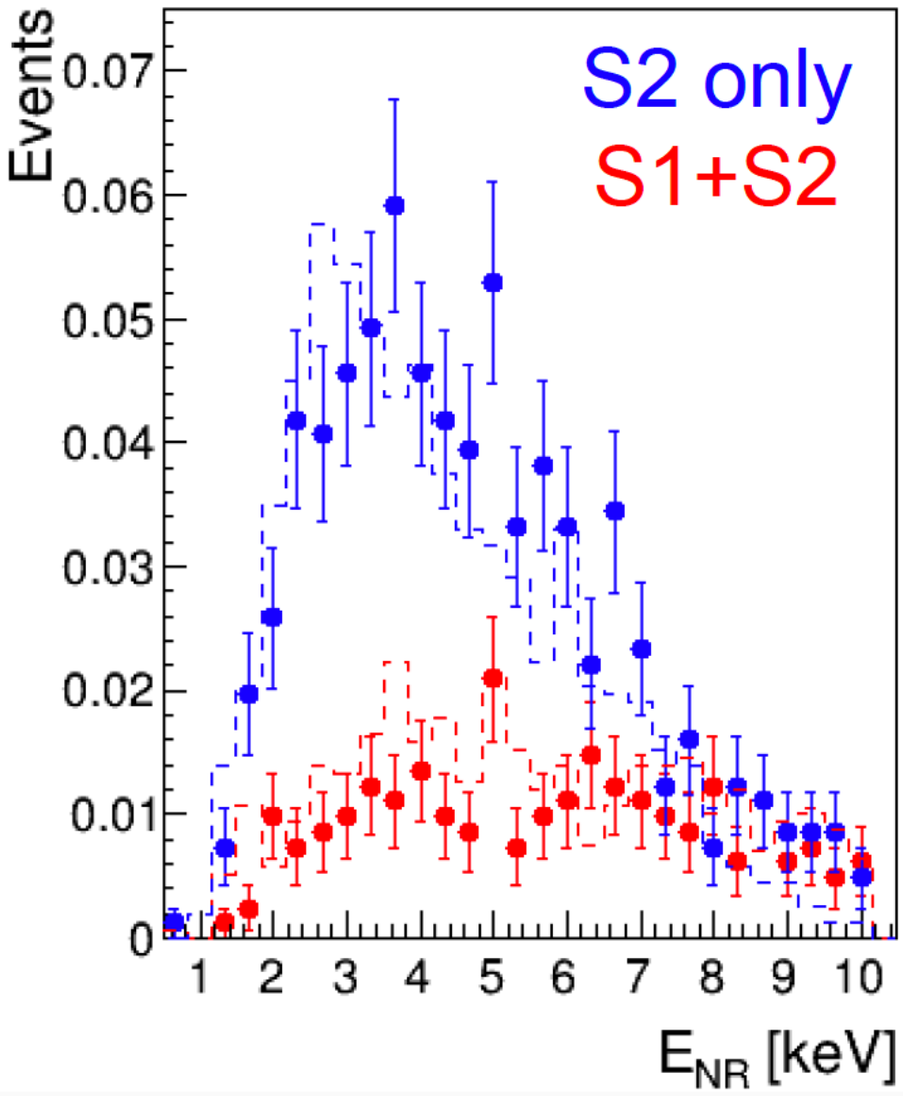


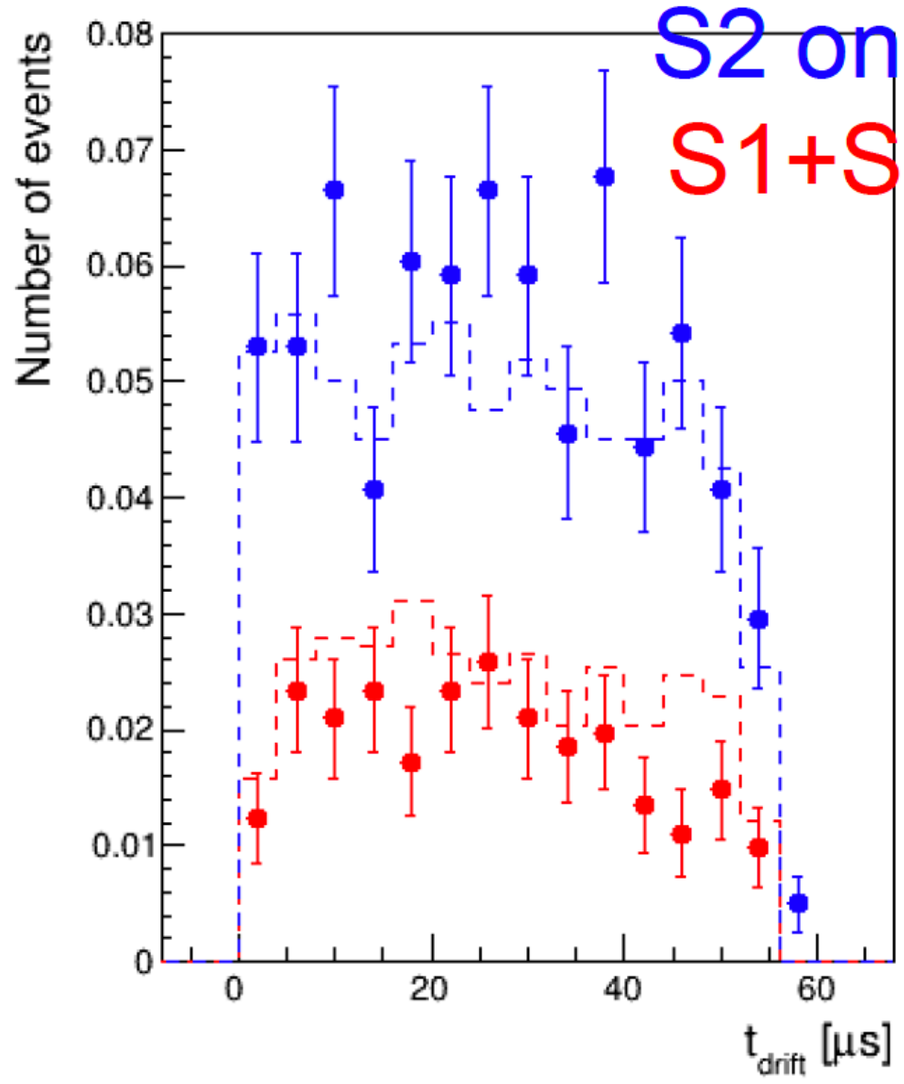


- ReD's next phase (ReD+) with a monoenergetic (2.5 MeV) neutron beam already moving on.
- NG being commissioned at University of São Paulo.
- New TPC being designed (Italian PRIN funding).
- Final setup to be operated at INFN LNS, Catania

Backups

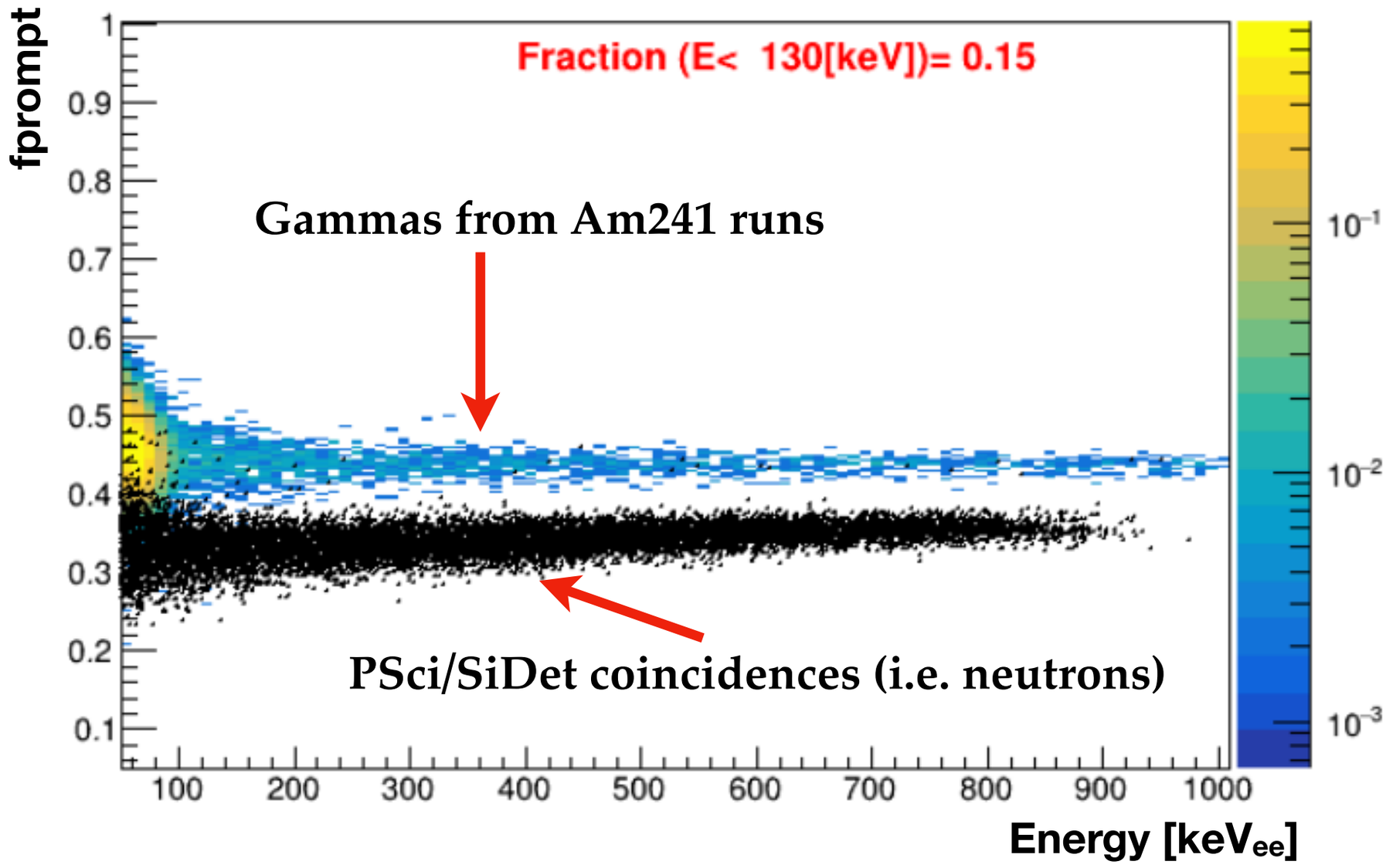
Data x MC comparisons





data

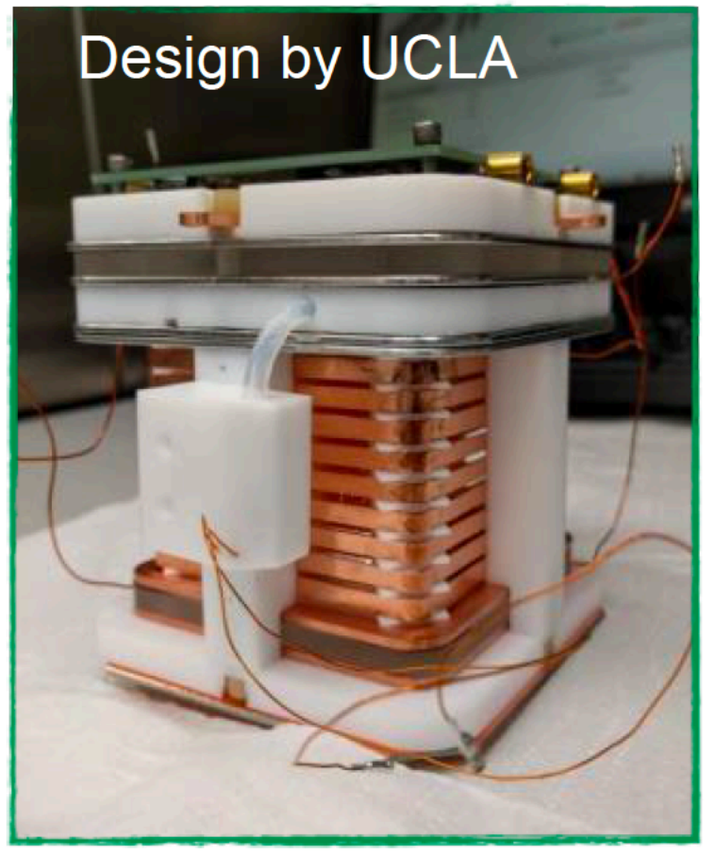
Monte Carlo

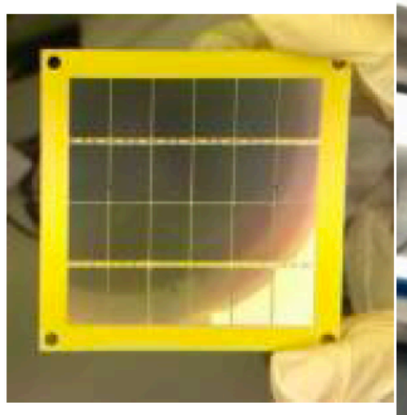

fprompt
Fraction (E< 130[keV])= 0.15
Gammas from Am241 runs
PSci/SiDet coincidences (i.e. neutrons)
Energy [keV$_{ee}$]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
100
200
300
400
500
600
700
800
900
1000
10^{-1}
10^{-2}
10^{-3}

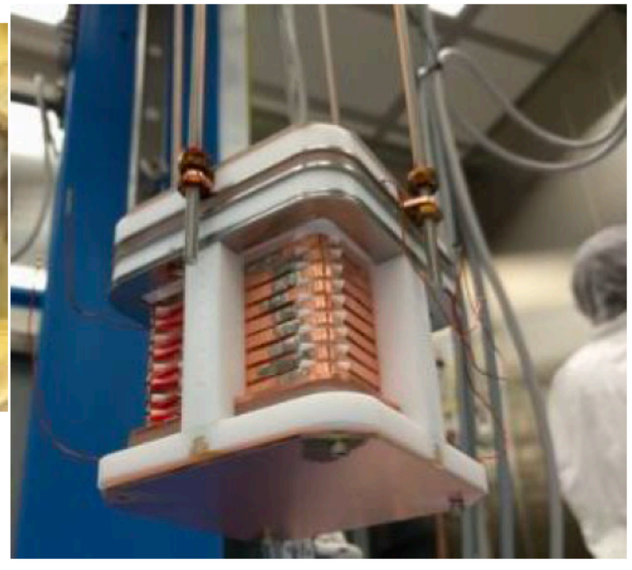
Credit for slide: Luciano Pandola

The TPC …

- **Miniaturized version** of the DS-20k TPC
  - Active volume: 5(L) x 5 (W) x 6 (H) cm
  - Gas pocket: 7 mm thick
  - TPB coating for wavelength shifting
- DS-20k light readout: **5x5 cm² SiPM**, 24x1cm² SiPM
  - 24 ch readout (top), for increased (x,y) resolution
  - 24x1cm² SiPM, 4 ch readout (bottom)
- **Front End** from the DS-20k R&D
- **3D event reconstruction:**
  - (x,y) from S2 pattern on the top SiPMs
  - z from **drift time** (up to ~55 μs)
- In this campaign:
  - g_2 = ~17 PE/e- (E_{drift} = 200 V/cm, E_{el}=5.79 kV/cm)
  - Electron lifetime > 1 ms







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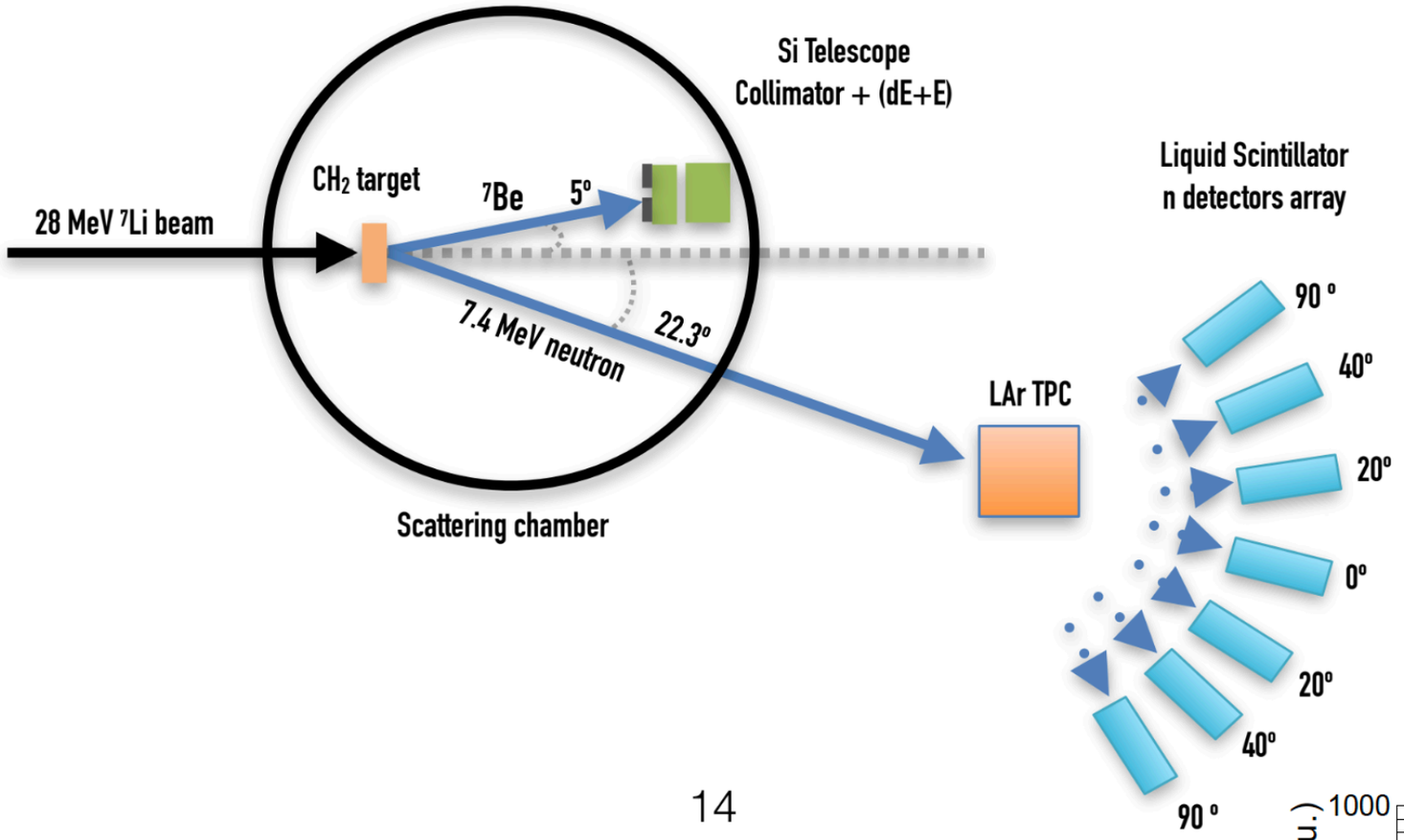
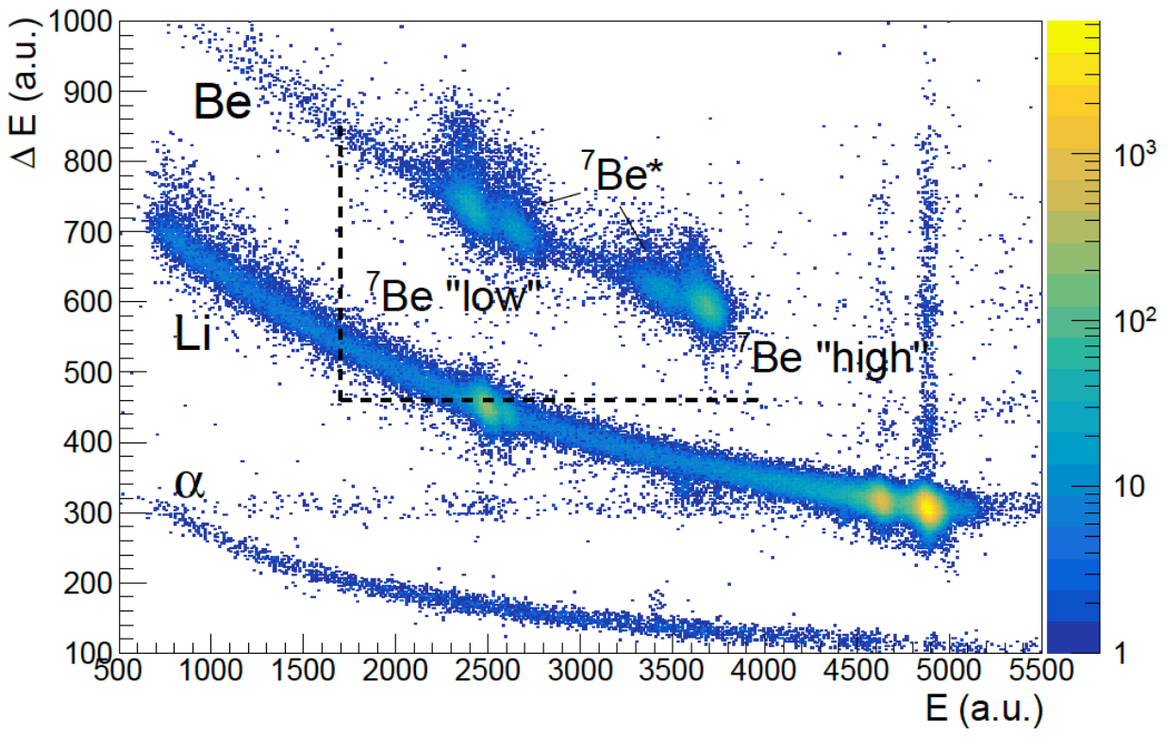
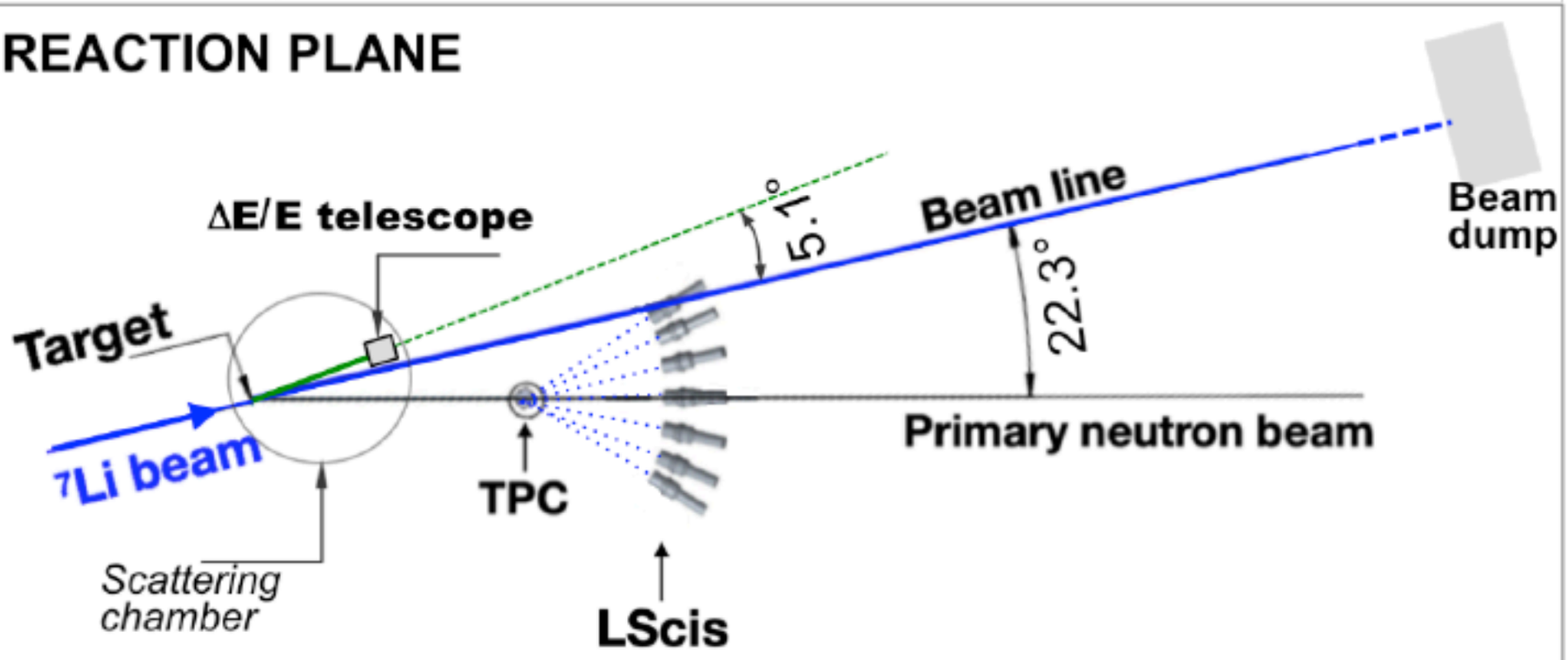
ReD's initial campaign

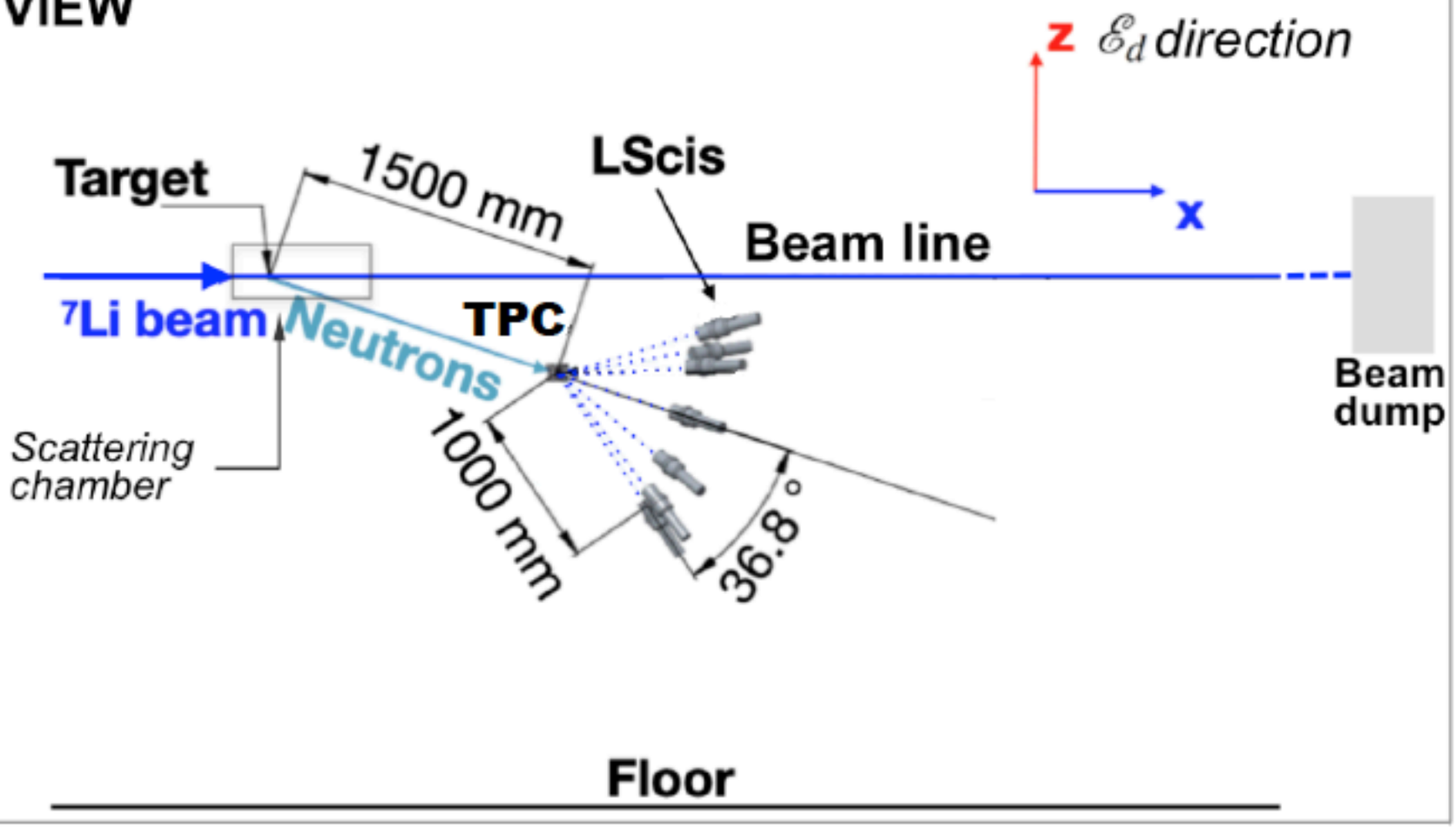


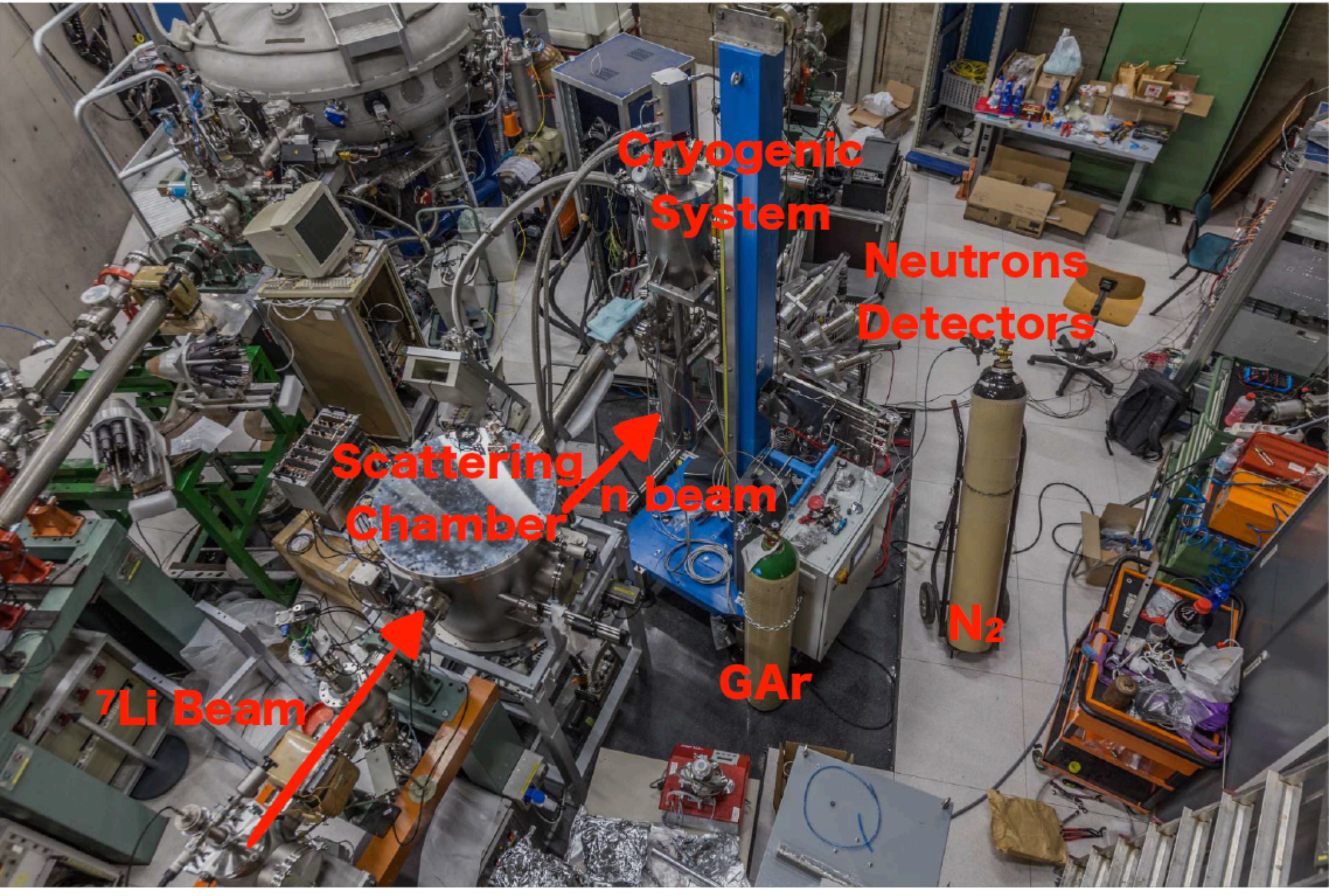


REACTION PLANE

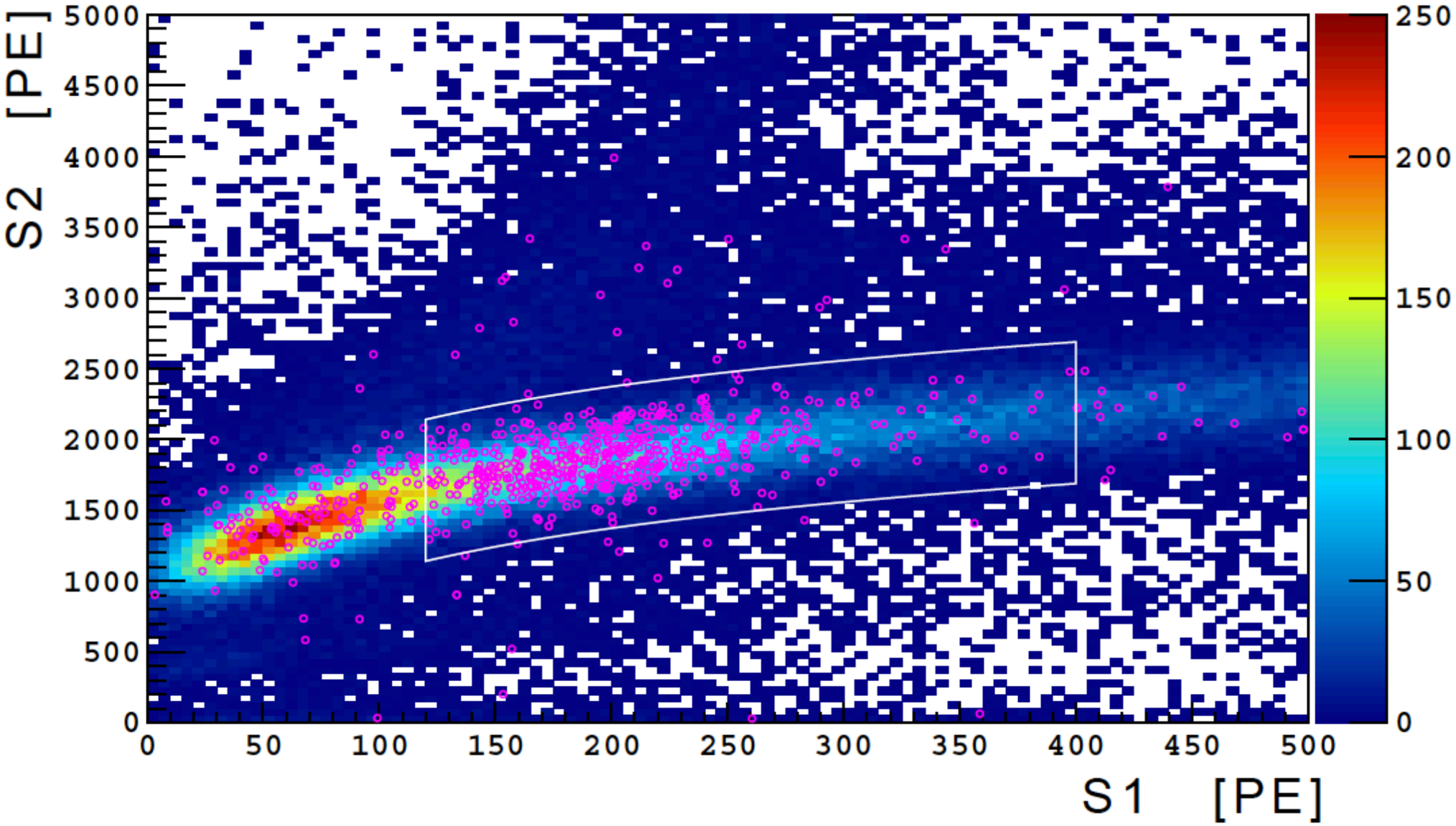


SIDE VIEW

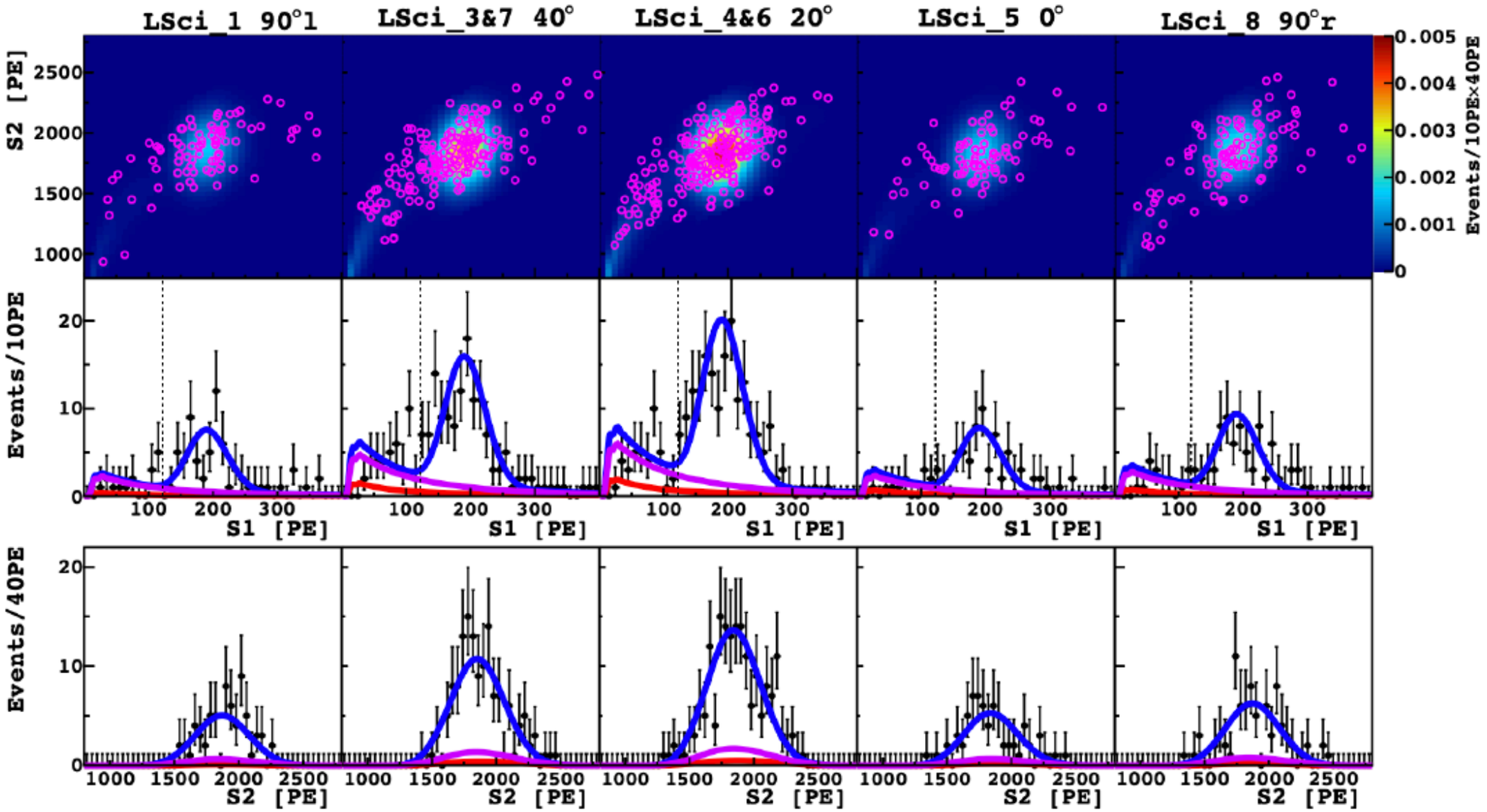



Cryogenic System
Neutrons Detectors
Scattering Chamber
n beam
^{7}Li Beam
GAr
N_2

S1 and S2 reconstruction from directionality campaign



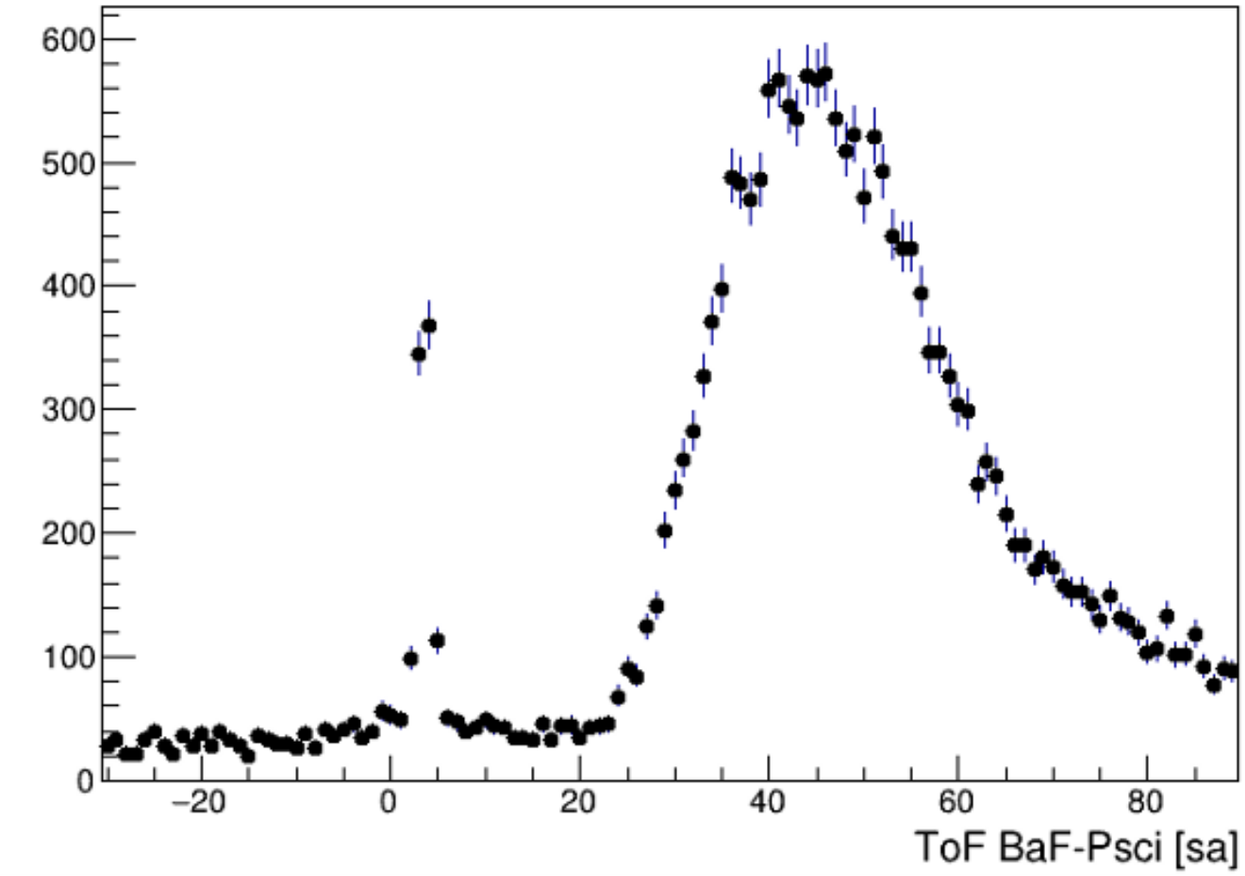
Searches for directionality

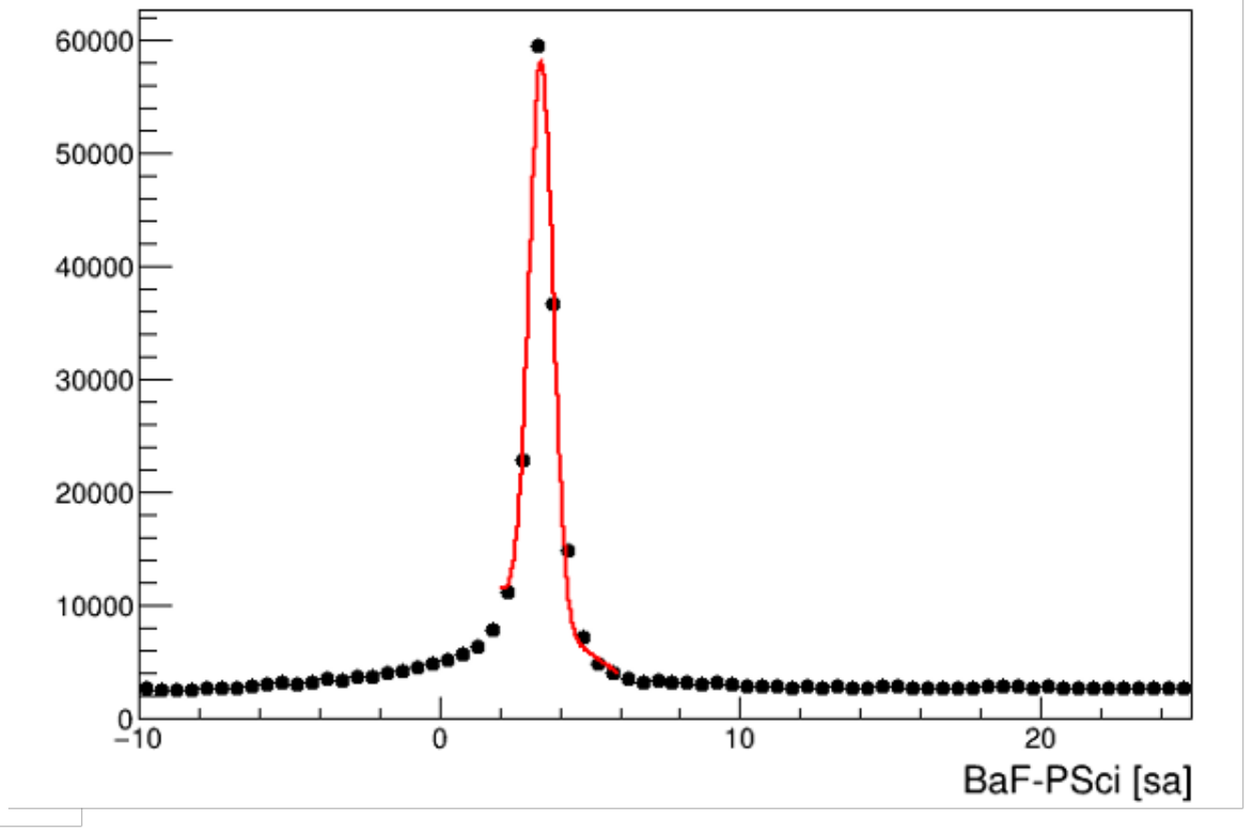


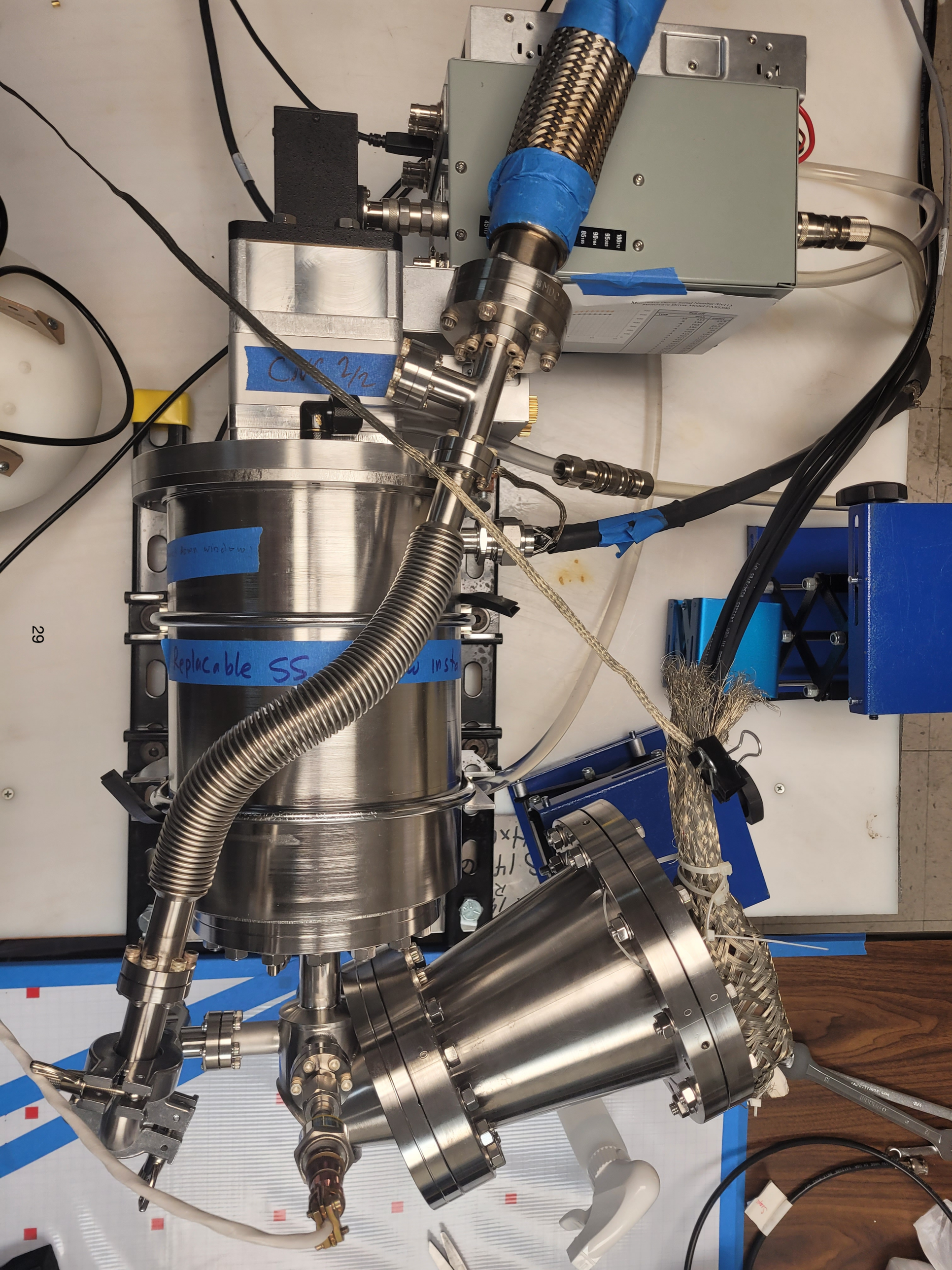
No indication of directionality

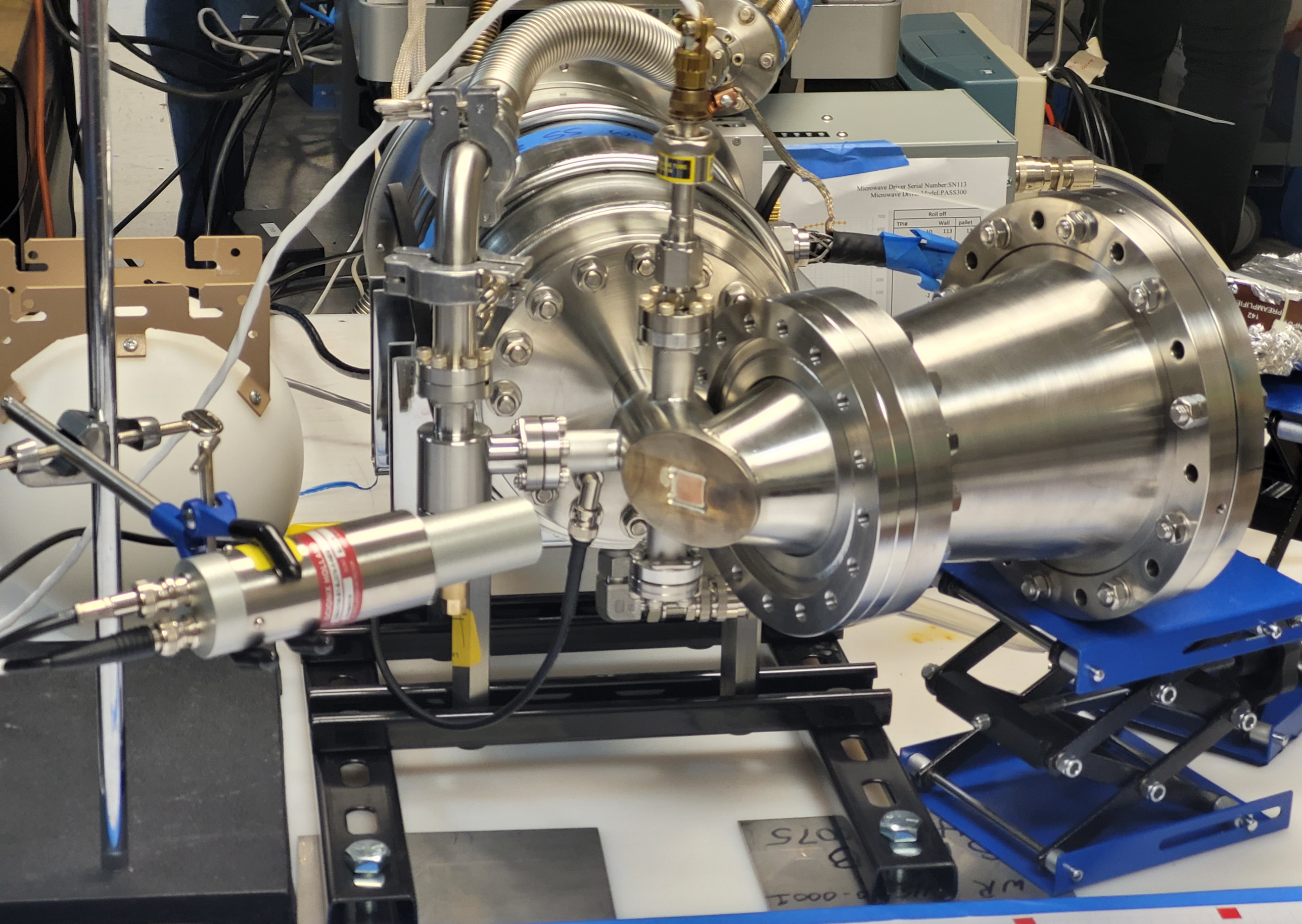
Parameter	Value	Correlation with δR
δR	0.037 ± 0.027	-
$A\,[1/e^-]$	$(4.01 \pm 0.06) \times 10^{-2}$	-0.014
g_1 [PE/ph]	0.204 ± 0.002	0.013
g_2 [PE/e^-]	20.1 ± 0.2	-0.009
$\sigma^*_{S1}/S1$	0.017 ± 0.003	-0.012
$\sigma^*_{S2}/S2$	0.0002 ± 0.0060	0.026

ToF distributions (252Cf campaign)

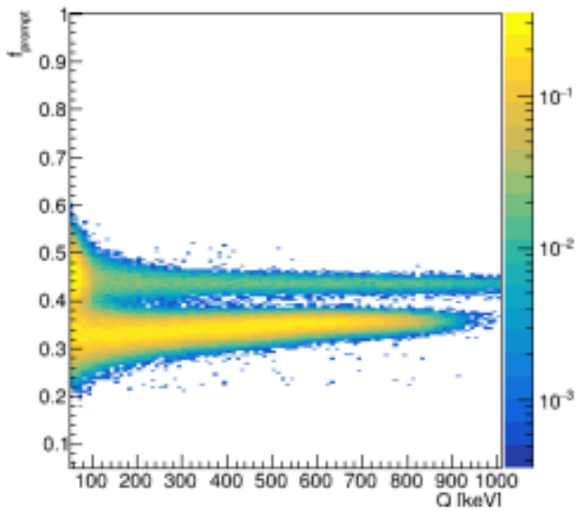


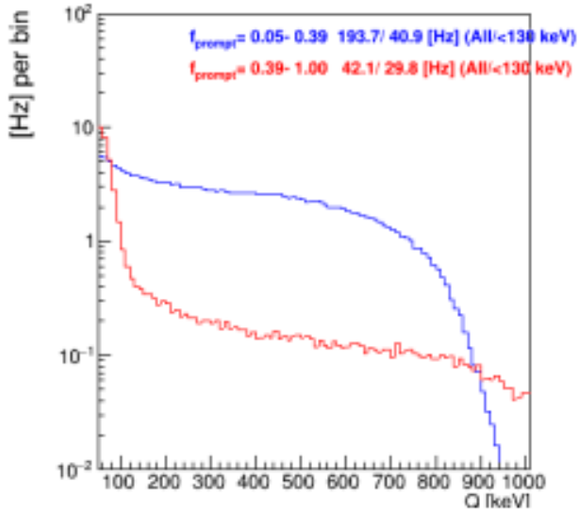


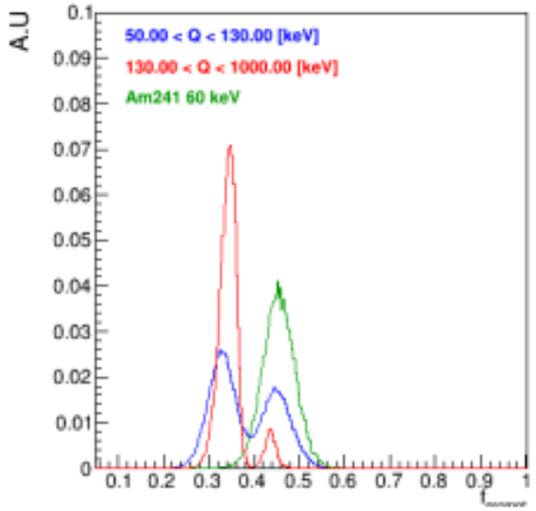

CNS 2/2
Replacable SS

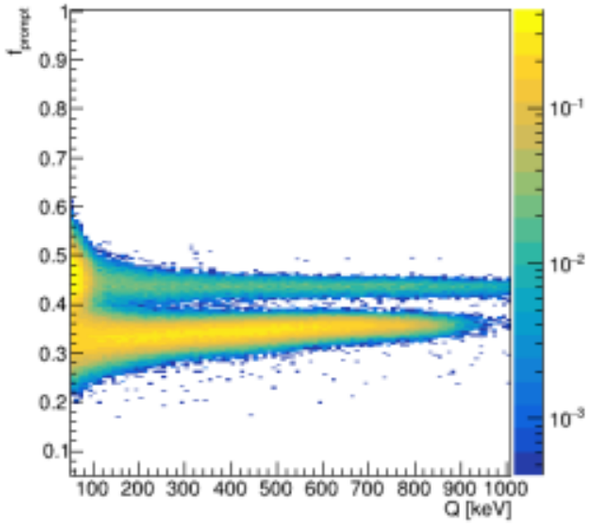

Microwave Driver Serial Number:SN113
Roll off
TPI#
Wall
pallet

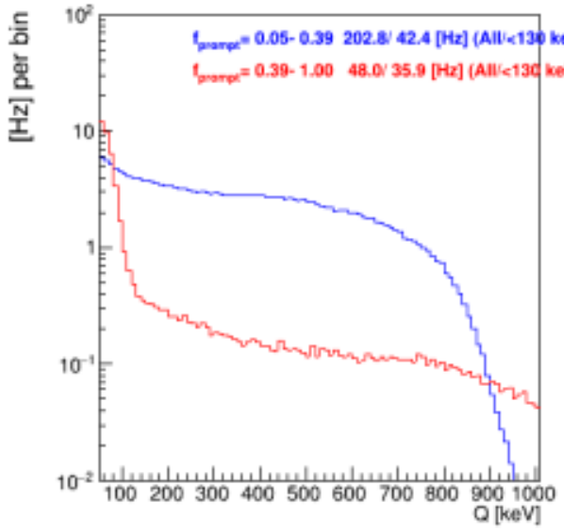
Run 134/139 ~9 cm from target

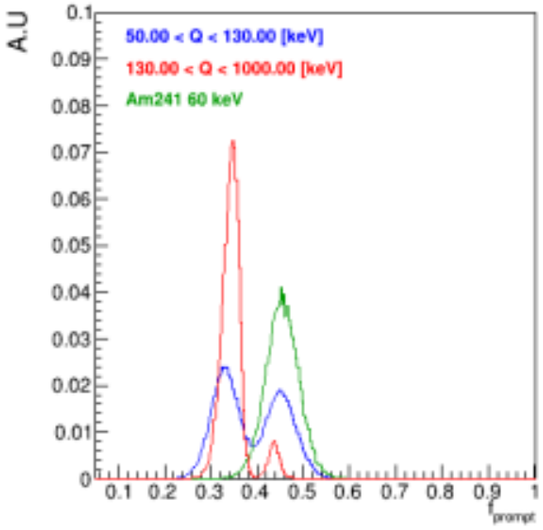




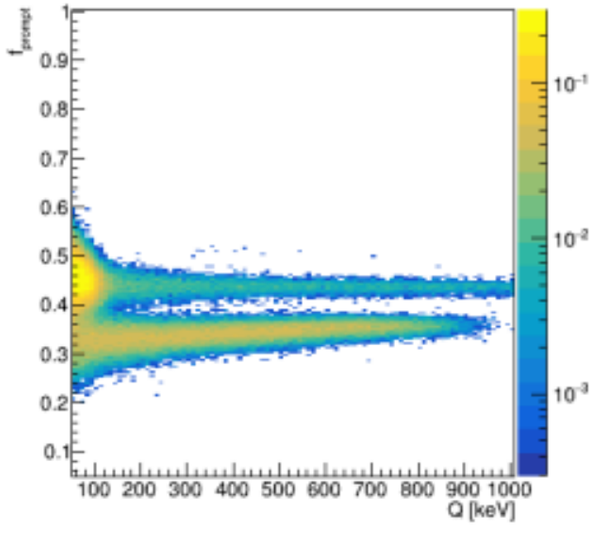


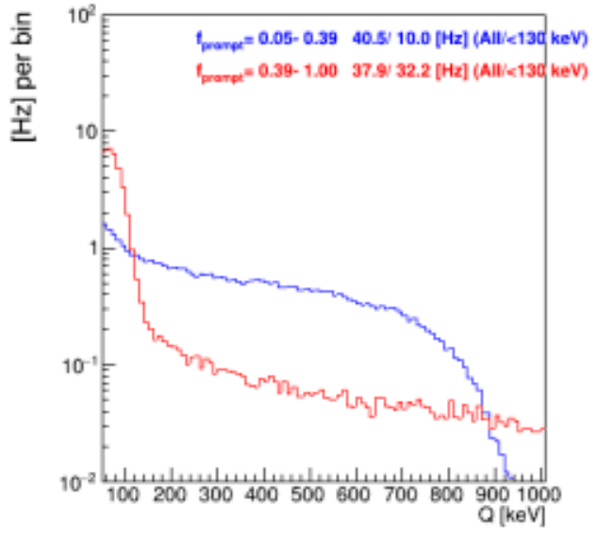


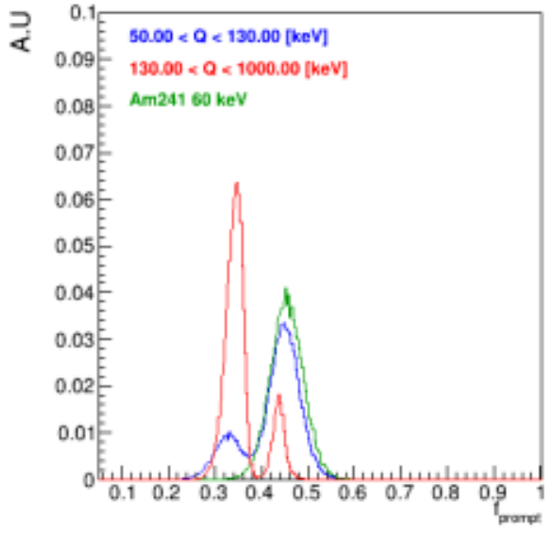


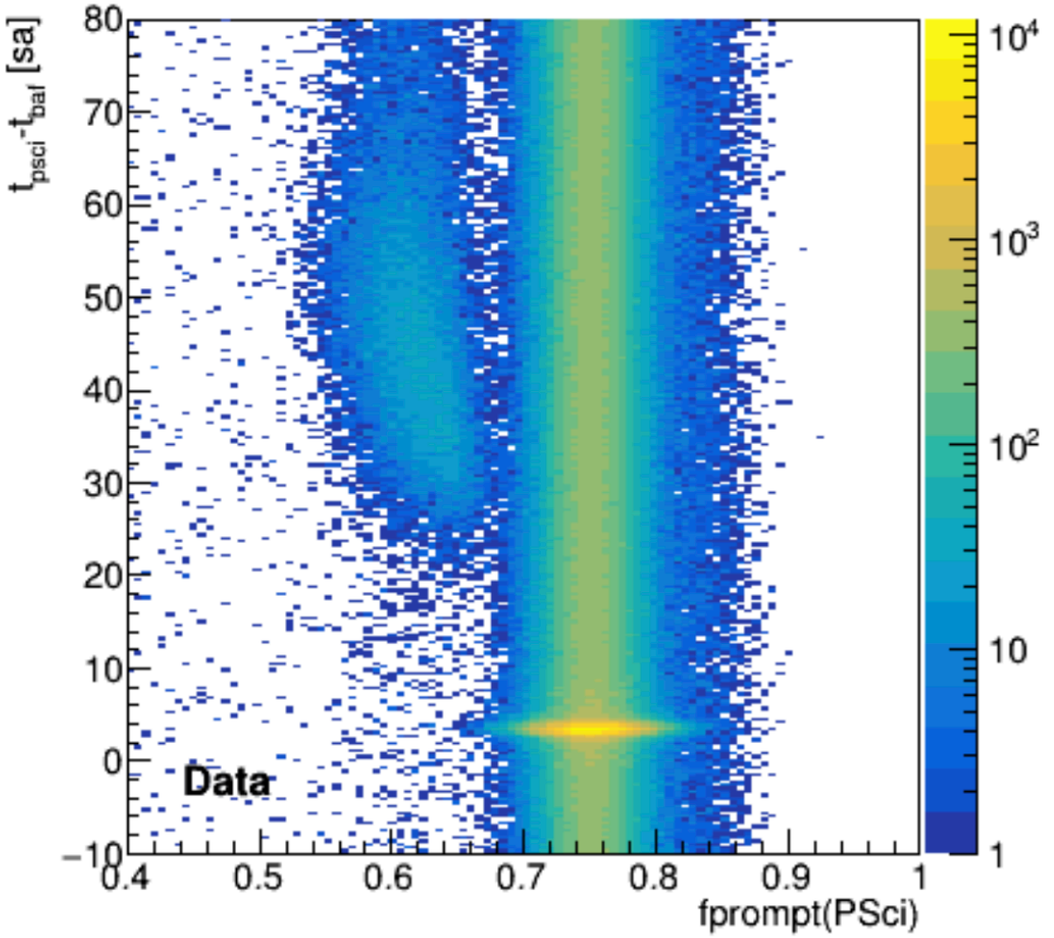


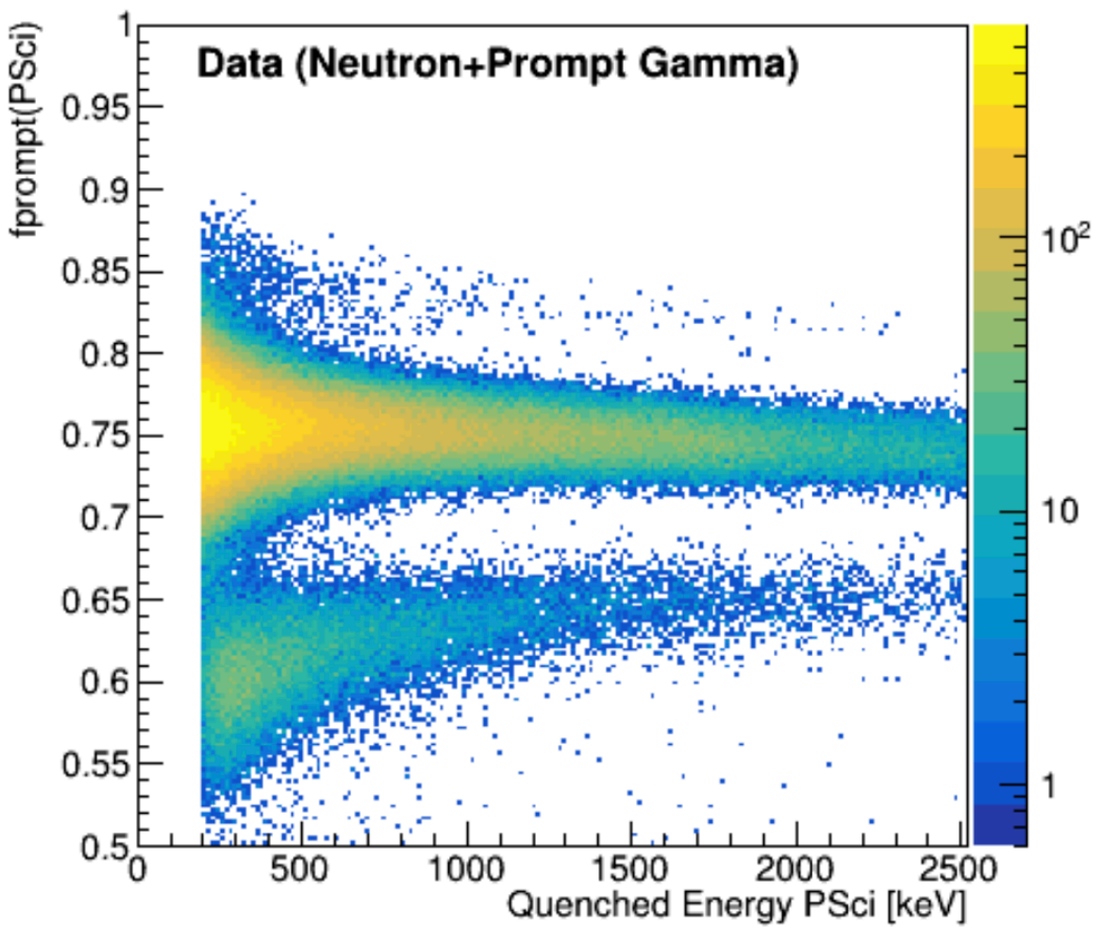
Run 147 ~27 cm from target

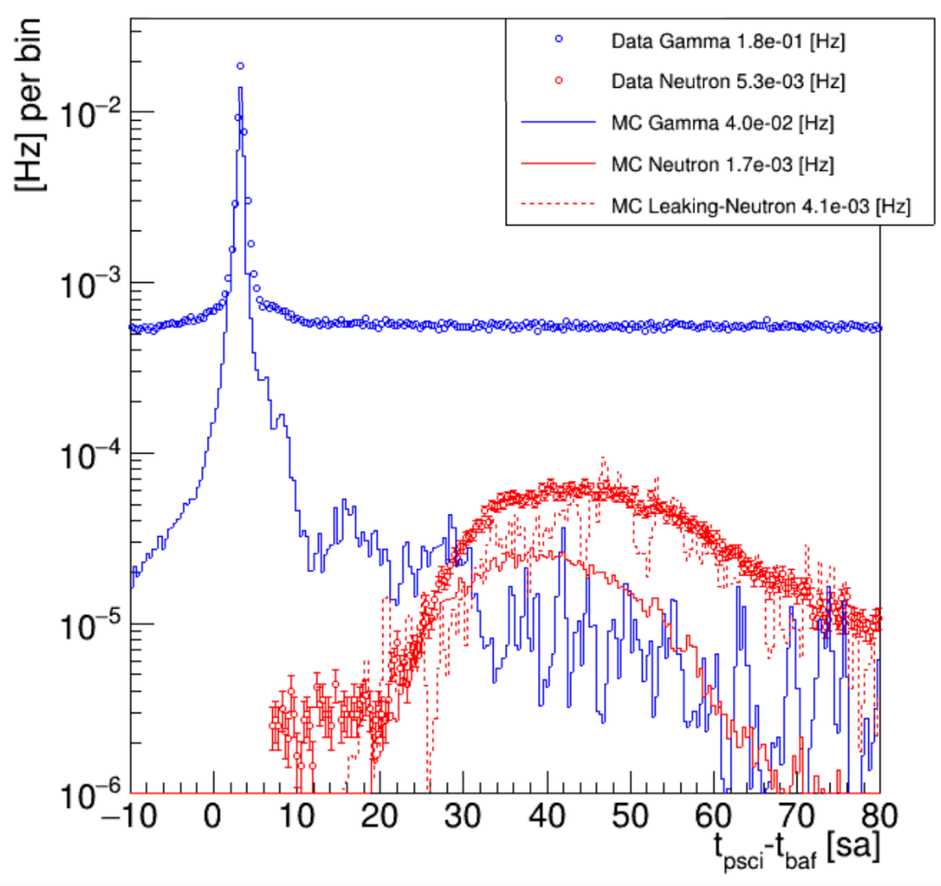







Data
t_{psci}-t_{baf} [sa]
fprompt(PSci)


Data (Neutron+Prompt Gamma)
fprompt(PSci)
Quenched Energy PSci [keV]


Data Gamma 1.8e-01 [Hz]
Data Neutron 5.3e-03 [Hz]
MC Gamma 4.0e-02 [Hz]
MC Neutron 1.7e-03 [Hz]
MC Leaking-Neutron 4.1e-03 [Hz]
[Hz] per bin
t_{psci}-t_{baf} [sa]